ANALYTICAL AND EXPERIMENTAL INVESTIGATION
OF FLOW FIELDS OF ANNULAR JETS
WITH AND WITHOUT SWIRLING FLOW

by

GENERAL ELECTRIC COMPANY

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Abstract

Analytical and experimental studies were performed to define the flowfield of annular jets, with and without swirling flow. The analytical model treated configurations with variations of flow angularities, radius ratio and swirl distributions. Swirl distributions characteristic of stator vanes and rotor blade rows, where the total pressure and swirl distributions are related were incorporated in the mathematical model.

The experimental studies included tests of eleven nozzle models, both with and without swirling exhaust flow. Flowfield surveys were obtained and used for comparison with the analytical model. This comparison of experimental and analytical studies served as the basis for evaluation of several empirical constants as required for application of the analysis to the general flow configuration.

The analytical model developed during these studies is applicable to the evaluation of the flowfield and overall performance of the exhaust of statorless lift fan systems that contain various levels of exhaust swirl.

Key Words

Lift Fans, Annular Jets,
Base Pressures, Swirl

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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>SUMMARY</td>
<td>1</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>2</td>
</tr>
<tr>
<td>ANALYTICAL INVESTIGATIONS</td>
<td>3</td>
</tr>
<tr>
<td>Analytical Model</td>
<td>3</td>
</tr>
<tr>
<td>General Discussion</td>
<td>3</td>
</tr>
<tr>
<td>Analysis</td>
<td>5</td>
</tr>
<tr>
<td>Assumptions and Boundary Conditions</td>
<td>5</td>
</tr>
<tr>
<td>General Approach</td>
<td>6</td>
</tr>
<tr>
<td>Mean Streamline Shape</td>
<td>7</td>
</tr>
<tr>
<td>Station Calculations Normal to Streamline</td>
<td>9</td>
</tr>
<tr>
<td>Streamline Curvatures</td>
<td>9</td>
</tr>
<tr>
<td>Summary of Other Equations</td>
<td>9</td>
</tr>
<tr>
<td>Axial Force Balance</td>
<td>10</td>
</tr>
<tr>
<td>Overall Performance Calculations</td>
<td>11</td>
</tr>
<tr>
<td>Computer Program</td>
<td>13</td>
</tr>
<tr>
<td>General Description</td>
<td>13</td>
</tr>
<tr>
<td>&quot;ROTFLO&quot; Subroutine</td>
<td>14</td>
</tr>
<tr>
<td>Iteration Scheme</td>
<td>14</td>
</tr>
<tr>
<td>Input Definitions</td>
<td>15</td>
</tr>
<tr>
<td>Output Definitions</td>
<td>16</td>
</tr>
<tr>
<td>EXPERIMENTAL INVESTIGATIONS</td>
<td>18</td>
</tr>
<tr>
<td>Test Hardware and Instrumentation</td>
<td>18</td>
</tr>
<tr>
<td>Base Pressure Models</td>
<td>18</td>
</tr>
<tr>
<td>Test Facility</td>
<td>18</td>
</tr>
<tr>
<td>Instrumentation</td>
<td>19</td>
</tr>
<tr>
<td>Testing and Procedures</td>
<td>20</td>
</tr>
<tr>
<td>Test Scope</td>
<td>20</td>
</tr>
<tr>
<td>Test Procedures</td>
<td>20</td>
</tr>
<tr>
<td>Probe Calibration</td>
<td>20</td>
</tr>
<tr>
<td>Data Processing</td>
<td>21</td>
</tr>
<tr>
<td>Test Results</td>
<td>22</td>
</tr>
<tr>
<td>Performance With Axial Flow</td>
<td>22</td>
</tr>
<tr>
<td>Performance With Swirling Flow</td>
<td>23</td>
</tr>
<tr>
<td>Performance With Variable Pressure Ratio</td>
<td>24</td>
</tr>
<tr>
<td>Performance With Blockage</td>
<td>25</td>
</tr>
<tr>
<td>Performance With Skewed Swirl Distribution</td>
<td>26</td>
</tr>
</tbody>
</table>
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>APPLICATION OF ANALYTICAL METHODS</td>
<td>27</td>
</tr>
<tr>
<td>CONCLUSIONS</td>
<td>30</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>32</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>38</td>
</tr>
<tr>
<td>APPENDIX I - DERIVATION OF EQUATIONS OF EQUILIBRIUM NORMAL TO A STREAMLINE</td>
<td>39</td>
</tr>
<tr>
<td>APPENDIX II - DATA ANALYSIS PROCEDURES</td>
<td>43</td>
</tr>
<tr>
<td>APPENDIX III - COMPUTER PROGRAM LISTING</td>
<td>46</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>TABLE</th>
<th>Description</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Base Pressure Model Descriptions</td>
<td>53</td>
</tr>
<tr>
<td>II</td>
<td>Inner and Outer Exit Contour Geometries of the Base Pressure Models</td>
<td>54</td>
</tr>
<tr>
<td>III</td>
<td>Test Run Summary</td>
<td>57</td>
</tr>
<tr>
<td>IV</td>
<td>Performance Comparisons for Axial, Swirling and Skewed Flow Distributions</td>
<td>58</td>
</tr>
<tr>
<td>V</td>
<td>Comparison of Test and Theory for Configurations SA2, SA6, SA10 and SE</td>
<td>59</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURES</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Analytical Model</td>
</tr>
<tr>
<td>2</td>
<td>Streamline Curvature Approximations</td>
</tr>
<tr>
<td>3</td>
<td>Computer Program Block Diagram</td>
</tr>
<tr>
<td>4</td>
<td>Secant Iteration Scheme</td>
</tr>
<tr>
<td>5</td>
<td>Photograph of the Base Pressure Model Assembly</td>
</tr>
<tr>
<td>6</td>
<td>Photograph of the Axial and Swirl Vane Assemblies</td>
</tr>
<tr>
<td>7</td>
<td>Hub Base Pressure Test Model Schematic</td>
</tr>
<tr>
<td>8</td>
<td>Photograph of the Base Pressure Model Installed in the Test Stand</td>
</tr>
<tr>
<td>9</td>
<td>Schematic of Exhaust Traverse Probe</td>
</tr>
<tr>
<td>10</td>
<td>Probe Calibration of Static Pressure</td>
</tr>
<tr>
<td>11</td>
<td>Total and Static Pressure Coefficient Distribution for Models 1 and 2, Axial Flow</td>
</tr>
<tr>
<td>12</td>
<td>Total and Static Pressure Coefficient Distribution for Models 3 and 4, Axial Flow</td>
</tr>
<tr>
<td>13</td>
<td>Total and Static Pressure Coefficient Distribution for Models 5 and 6, Axial Flow</td>
</tr>
<tr>
<td>14</td>
<td>Total and Static Pressure Coefficient Distribution for Models 7 and 8, Axial Flow</td>
</tr>
<tr>
<td>15</td>
<td>Total and Static Pressure Coefficient Distribution for Models 9 and 10, Axial Flow</td>
</tr>
<tr>
<td>16</td>
<td>Total and Static Pressure Coefficient Distribution for Model E, Axial Flow</td>
</tr>
<tr>
<td>17</td>
<td>Total and Static Pressure Coefficient Distribution for Models 1 and 2, Axial Flow</td>
</tr>
<tr>
<td>18</td>
<td>Total and Static Pressure Coefficient Distribution for Models 3 and 4, Axial Flow</td>
</tr>
<tr>
<td>19</td>
<td>Total and Static Pressure Coefficient Distribution for Models 5 and 6, Axial Flow</td>
</tr>
<tr>
<td>20</td>
<td>Total and Static Pressure Coefficient Distribution for Models 7 and 8, Axial Flow</td>
</tr>
<tr>
<td>21</td>
<td>Total and Static Pressure Coefficient Distribution for Models 9 and 10, Axial Flow</td>
</tr>
<tr>
<td>22</td>
<td>Total and Static Pressure Coefficient Distribution for Model E, Axial Flow</td>
</tr>
<tr>
<td>23</td>
<td>Graphical Representation of the Flow Field for Model 1 and 2, Axial Flow</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>24</td>
<td>Graphical Representation of the Flow Field for Models 3 and 4, Axial Flow</td>
</tr>
<tr>
<td>25</td>
<td>Graphical Representation of the Flow Field for Models 5 and 6, Axial Flow</td>
</tr>
<tr>
<td>26</td>
<td>Graphical Representation of the Flow Field for Models 7 and 8, Axial Flow</td>
</tr>
<tr>
<td>27</td>
<td>Graphical Representation of the Flow Field for Models 9 and 10, Axial Flow</td>
</tr>
<tr>
<td>28</td>
<td>Graphical Representation of the Flow Field for Model E, Axial Flow</td>
</tr>
<tr>
<td>29</td>
<td>Flow Entrainment Characteristics for Models 1 through 4, Axial Flow</td>
</tr>
<tr>
<td>30</td>
<td>Flow Entrainment Characteristics for Models 5 through 8, Axial Flow</td>
</tr>
<tr>
<td>31</td>
<td>Flow Entrainment Characteristics for Models 9, 10 and AE, Axial Flow</td>
</tr>
<tr>
<td>32</td>
<td>Wake Mixing Loss Characteristics for Models A1 through A4, Axial Flow</td>
</tr>
<tr>
<td>33</td>
<td>Wake Mixing Loss Characteristics for Models 5 through 8, Axial Flow</td>
</tr>
<tr>
<td>34</td>
<td>Wake Mixing Loss Characteristics for Models 9, 10 and AE, Axial Flow</td>
</tr>
<tr>
<td>35</td>
<td>Effects of Geometry on Average Hub Base Pressure, Axial Flow</td>
</tr>
<tr>
<td>36</td>
<td>Effects of Geometry on Main Flow Thrust Coefficient, Axial Flow</td>
</tr>
<tr>
<td>37</td>
<td>Effects of Geometry on Overall Thrust, Axial Flow</td>
</tr>
<tr>
<td>38</td>
<td>Effects of Geometry on Flow Coefficient, Axial Flow</td>
</tr>
<tr>
<td>39</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 1 and 2, Swirling Flow, Close-up Traverse Position</td>
</tr>
<tr>
<td>40</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 3 and 4, Swirling Flow, Close-Up Traverse Position</td>
</tr>
<tr>
<td>41</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 5 and 6, Swirling Flow, Close-Up Traverse Position</td>
</tr>
<tr>
<td>42</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 7 and 8, Swirling Flow, Close-Up Traverse Position</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>43</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 9 and 10, Swirling Flow, Close-Up Traverse Position</td>
</tr>
<tr>
<td>44</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models E, Swirling Flow, Close-Up Traverse Position</td>
</tr>
<tr>
<td>45</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 1 and 2, Swirling Flow, Downstream Traverse Location</td>
</tr>
<tr>
<td>46</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 3 and 4, Swirling Flow, Downstream Traverse Location</td>
</tr>
<tr>
<td>47</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 5 and 6, Swirling Flow, Downstream Traverse Location</td>
</tr>
<tr>
<td>48</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 7 and 8, Swirling Flow, Downstream Traverse Location</td>
</tr>
<tr>
<td>49</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 9 and 10, Swirling Flow, Downstream Traverse Location</td>
</tr>
<tr>
<td>50</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Model E, Swirling Flow, Downstream Traverse Location</td>
</tr>
<tr>
<td>51</td>
<td>Graphical Representation of the Flow Field for Models 1 and 2, Swirling Flow</td>
</tr>
<tr>
<td>52</td>
<td>Graphical Representation of the Flow Field for Models 3 and 4, Swirling Flow</td>
</tr>
<tr>
<td>53</td>
<td>Graphical Representation of the Flow Field for Models 5 and 6, Swirling Flow</td>
</tr>
<tr>
<td>54</td>
<td>Graphical Representation of the Flow Field for Models 7 and 8, Swirling Flow</td>
</tr>
<tr>
<td>55</td>
<td>Graphical Representation of the Flow Field for Models 9 and 10, Swirling Flow</td>
</tr>
<tr>
<td>56</td>
<td>Graphical Representation of the Flow Field for Model E, Swirling Flow</td>
</tr>
<tr>
<td>57</td>
<td>Flow Entrainment Characteristics for Models 5 through 8, Swirling Flow</td>
</tr>
<tr>
<td>58</td>
<td>Flow Entrainment Characteristics for Models 1 through 4, Swirling Flow</td>
</tr>
<tr>
<td>59</td>
<td>Flow Entrainment Characteristics for Models 9, 10, and E, Swirling Flow</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>60</td>
<td>Wake Mixing Loss Characteristics for Models 1 through 4, Swirling Flow</td>
</tr>
<tr>
<td>61</td>
<td>Wake Mixing Loss Characteristics for Models 5 through 8, Swirling Flow</td>
</tr>
<tr>
<td>62</td>
<td>Wake Mixing Loss Characteristics for Models 9, 10 and SE, Swirling Flow</td>
</tr>
<tr>
<td>63</td>
<td>Effects of Geometry on Average Hub Base Pressure, Swirling Flow</td>
</tr>
<tr>
<td>64</td>
<td>Effects of Geometry on the Hub Outer Radius Base Pressure Coefficient, $\beta = 10$ &amp; 0, Swirling Flow</td>
</tr>
<tr>
<td>65</td>
<td>Effects of Geometry on the Hub Outer Radius Base Pressure Coefficient, $\beta = -10$ &amp; -20, Swirling Flow</td>
</tr>
<tr>
<td>66</td>
<td>Effects of Geometry on Main Flow Thrust, Swirling Flow</td>
</tr>
<tr>
<td>67</td>
<td>Effects of Geometry on Overall Thrust, Swirling Flow</td>
</tr>
<tr>
<td>68</td>
<td>Effects of Geometry on Flow Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>69</td>
<td>Effects of Pressure Ratio on Total and Static Pressure Coefficients and Swirl Distribution for Model 2, Swirling Flow</td>
</tr>
<tr>
<td>70</td>
<td>Effects of Pressure Ratio on Total and Static Pressure Coefficients and Swirl Distribution for Model 6, Swirling Flow</td>
</tr>
<tr>
<td>71</td>
<td>Effects of Pressure Ratio on Total and Static Pressure Coefficients and Swirl Distribution for Model 10, Swirling Flow</td>
</tr>
<tr>
<td>72</td>
<td>Effects of Pressure Ratio on the Average Hub Base Pressure Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>73</td>
<td>Effects of Pressure Ratio on the Hub Outer Radius Base Pressure Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>74</td>
<td>Effects of Pressure Ratio on the Main Flow Thrust Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>75</td>
<td>Effects of Pressure Ratio on the Overall Thrust Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>76</td>
<td>Effects of Pressure Ratio on the Flow Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>77</td>
<td>Photograph of the Blockage System Installed in the Test Stand</td>
</tr>
<tr>
<td>FIGURE</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients for Model 2, Axial Flow</td>
</tr>
<tr>
<td>--------</td>
<td>---------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>78</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients for Model 6, Axial Flow</td>
</tr>
<tr>
<td>79</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients for Model 10, Axial Flow</td>
</tr>
<tr>
<td>80</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients for Models 2, 6 and 10, Axial Flow</td>
</tr>
<tr>
<td>81</td>
<td>Effects of Blockage on the Base Pressure and Flow Coefficient for Model 2, Swirling Flow</td>
</tr>
<tr>
<td>82</td>
<td>Effects of Blockage on the Base Pressure and Flow Coefficient for Models 6, Swirling Flow</td>
</tr>
<tr>
<td>83</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients and Swirl Distribution for Model 2, Swirling Flow</td>
</tr>
<tr>
<td>84</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients and Swirl Distribution for Model 6, Swirling Flow</td>
</tr>
<tr>
<td>85</td>
<td>Effects of Blockage on Total and Static Pressure Coefficients and Swirl Distribution for Model 10, Swirling Flow</td>
</tr>
<tr>
<td>86</td>
<td>Effects of Blockage on the Base Pressure Coefficients, Swirling Flow</td>
</tr>
<tr>
<td>87</td>
<td>Effects of Blockage on the Flow Coefficient, Swirling Flow</td>
</tr>
<tr>
<td>88</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Model 2, Skewed Flow Distribution</td>
</tr>
<tr>
<td>89</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Model 6, Skewed Flow Distribution</td>
</tr>
<tr>
<td>90</td>
<td>Total and Static Pressure Coefficient and Swirl Angle Distribution for Model 10, Skewed Flow Distribution</td>
</tr>
<tr>
<td>91</td>
<td>Angular Momentum Distribution From Test</td>
</tr>
<tr>
<td>92</td>
<td>Wake Area Coefficient</td>
</tr>
<tr>
<td>93</td>
<td>Comparison of Theoretical Predictions to Test Results for the Base Pressure, Flow and Thrust Coefficients, RH/RT = 0.40, Swirling Flow</td>
</tr>
<tr>
<td>94</td>
<td>Comparison of Theoretical Predictions to Test Results for the Base Pressure, Flow and Thrust Coefficients, RH/RT = 0.55, Swirling Flow</td>
</tr>
<tr>
<td>FIGURE</td>
<td>PAGE</td>
</tr>
<tr>
<td>--------</td>
<td>------</td>
</tr>
<tr>
<td>95</td>
<td>154</td>
</tr>
<tr>
<td>96</td>
<td>155</td>
</tr>
<tr>
<td>97</td>
<td>156</td>
</tr>
<tr>
<td>98</td>
<td>157</td>
</tr>
</tbody>
</table>
SUMMARY

This is the final report presenting the results of the analytical and experimental investigations of flow fields downstream of annular jets, both with axial and swirling flows.

An analytical model was developed to predict the base pressures established by axial or swirling flow through annular jets having blunt bases. The model made predictions for configurations having various flow angularities, radius ratios and swirl distributions. Approximately 50 hours of scale model testing were conducted to determine several empirical constants that were required for the analytical model.

The scale models tested consisted of 11 sets of interchangeable inner and outer exhaust flowpaths encompassing flow angles of 10 degrees radially outward to 20 degrees radially inward and radius ratios of 0.40 to 0.70. All of the models were designed to have a constant nozzle exit area of 6.41 square inches (41.35 square centimeters). Various model configurations were tested with:

- Axial flow
- Swirling flow
- Variable pressure ratio
- Simulated louvers (blockage)
- Skewed flow distribution

Having evaluated the necessary empirical constants using the experimental results from the configurations tested with axial and swirling flows, a comparison of the theory with test results was made to verify the selection of the constants. A fair agreement was obtained considering the relatively small sampling of test configurations and the complexity of the analysis. Based on the comparison of test and analytical parameters such as velocity, flow and pressure coefficients, the analytical model appears to be an adequate representation of the exhaust flow downstream of annular nozzle with blunt bases.
INTRODUCTION

During the initial testing of a rotor-alone turbotip lift fan system, a deficiency in fan thrust was observed and identified as an excessively low hub base pressure. A program was initiated under NASA Contract NAS2-5462 to investigate, both analytically and experimentally, the effects of various types of flow fields upon the base pressures of an annular jet. This report covers this investigation.

An analytical model was developed to predict the level of base pressures which would exist for various flow angularities and nozzle exit radius ratios of annular jets. The analytical model was supported by approximately 50 hours of scale model testing conducted as a General Electric Company, Evendale test facility. Empirical constants from the experimental results were evaluated and used to verify the analytical results with the experimental results. Two of the test configurations were used as an independent check on the validity of the empirical constant selection.

Based on the comparison of test and analytical parameters such as velocity, flow and base pressure coefficients, the analytical model appears to be an adequate representation of the exhaust flow downstream of annular nozzles.
Analytical Investigations

Analytical Model

General Discussion

When flow exits from an annular nozzle with a blunt centerbody, the pressure over the aft face of the centerbody may be considerably different from the ambient pressure into which the jet is exhausting. This base pressure may have a significant effect on the flow and thrust coefficients of the nozzle. If the jet exits axially without swirl base pressure coefficients, based on average jet velocity head, on the order of -0.10 to -0.15 are typical. However, if the jet has radial or circumferential velocity components, it is found that the base pressure coefficients may vary widely from these values. This analysis was undertaken to develop an analytical model which could be used to predict base pressure, thrust, and flow coefficients for annular nozzles with nonaxial exit flow. The analysis also considers the effects of radial distribution of swirl, nozzle radius ratio and nozzle pressure ratio.

Conceptually, the reduction of the base pressure below ambient pressure can be thought of as being the result of three separate factors. First, in a jet with axial exit velocity, the shear forces between the high velocity main stream flow and the relatively stagnant air mass composing the centerbody wake must be balanced by an equal and opposite force acting across the base area. This component of base pressure is a true drag force and results in a thrust loss.

Second, there is a component of base pressure due to the meridonal curvature of the flow streamlines in the vicinity of the nozzle exit. This streamline curvature causes a radial static pressure gradient in the flow and, thus causes the base pressure to differ from ambient pressure. If the flow exits axially, the streamline curvatures are small; but if the flow is angled radially inward or outward, the streamline curvatures are much larger, and the effect on the base pressure may be significant. This component of the base pressure has no effect on the nozzle velocity coefficient since it is essentially a potential flow phenomenon.
Third, if the jet has a swirl velocity component, a radial pressure gradient must exist in the flow stream to support the centrifugal forces generated by the swirl. This then results in a base pressure lower than the ambient pressure. Furthermore, the swirling jet induces a rotational motion to the centerbody wake which in turn causes a radial pressure gradient across the base area and a further reduction in average base pressure. This component of base pressure can cause a large loss in nozzle thrust coefficient and represents the energy lost in the swirl velocity component.

It is evident that the above three effects are closely interrelated so that they cannot be treated independently in a mathematical analysis of the problem; however, it is conceptually enlightening to recognize the separate factors affecting the base pressure.
ANALYSIS

Assumptions and Boundary Conditions

Figure 1 shows the general scheme of the flow model assumed in this analysis. The flow downstream of the nozzle exit is divided into two distinct regions, the main stream flow and the centerbody wake. The dividing line between these two regions is the hub streamline of the main flow. It is recognized that there is actually flow interchange across this boundary, but it can be taken as the line across which the time averaged flow is zero. Thus, the total time averaged mass of air within the wake region is constant. It is assumed that static pressures in the two regions are equal along this streamline and that shear forces between the two regions may exist along this line.

The outer streamline of the main flow is assumed to be an isobaric surface where the static pressure equals the ambient pressure into which the jet is exhausting. Shear stresses and mixing along this outer boundary are assumed to have negligible effect on the base pressure of the centerbody.

At Station 1, the upstream boundary of the main flow, it is assumed that the radial distributions of total pressure, total temperature and angular momentum can be specified as will be explained later. At Station 2, the downstream boundary of the main flow, it is assumed that the slope and curvature of all streamlines are zero. Total temperature and swirl angle distributions at this station are derived from the upstream values assuming that energy and angular momentum are conserved along each streamline. The total pressure distribution at Station 2 is derived from the upstream total pressure and the assumption that the loss due to the shear stress between the main flow and wake is distributed uniformly across the main stream.

Other assumptions are that the flow is steady, axisymmetric and has the properties of an ideal gas. At the inlet station, it is assumed that the radial distribution of angular momentum can be sufficiently well represented as a linear relationship to the stream function.
General Approach

The general approach used in this analysis is as follows:

First, it is assumed that the shape of the 50% streamline can be represented by an exponential equation of the form.

\[ R_m = [A + B \left( \frac{Z}{L} \right) + C \left( \frac{Z}{L} \right)^2] e^{-\left( \frac{Z}{L} \right)} + R_m^2 \]  \hspace{1cm} (1)

It is readily seen that A and B are determined by the initial radius and slope of the 50% streamline. The constants C and \( R_m^2 \) are determined empirically and will be explained in more detail later. L is a length parameter that controls the rate at which \( R_m \) approaches its asymptotic value, \( R_m^2 \), and will be adjusted during the solution to satisfy axial momentum requirements.

- Starting with an initial guess for \( L \), the radius, slope and curvature of 50% streamline are calculated at a series of axial locations starting with \( Z = 0 \) and continuing until \( R_m \) approaches \( R_m^2 \) sufficiently close.

- An initial guess for the mass flow rate, \( M \), is then made, and at each of the above axial locations, a calculation is made along a line normal to the 50% streamline to determine flow properties and radial locations of the other main flow streamlines. Appendix I discusses the equations used for this calculation and the computer program section of this report discusses some of the calculation details. Briefly, however, good approximations to the streamline curvatures are made from the mean streamline slope and curvature and then the equations of momentum, continuity and energy are applied in a direction normal to the flow while satisfying the boundary condition of ambient static pressure on the outer streamline. These calculations begin at the nozzle exit and progress downstream and add an incremental total pressure loss at each step to account for the centerbody wake mixing loss. This incremental pressure loss is calculated from the local hub streamline velocity, density and incremental mixing surface area. This loss is assumed to be distributed uniformly through the main flow at each axial station however.
Next, using the static pressures and velocities calculated above, axial components of the pressure and momentum forces are integrated across the upstream Station 1 and the downstream Station 2. The pressure forces across the wake area are calculated using the hub streamline static pressures and an empirical correction based on the level of swirl at the hub streamline. The momentum forces across the wake areas are zero since the net amount of fluid in the wake does not change.

A check is then made on the overall balance between axial pressure and momentum forces acting on the fluid contained between Stations 1 and 2. The radius ratio at the nozzle exit station is also compared to the desired radius ratio. If the axial force balance and radius ratio are not close enough, new estimates are made for \( L \) and \( M \) and the procedure is repeated until the parameters are in agreement within a specified tolerance.

It is readily seen that the mass flow rate, \( M \), has a first order effect on the radius ratio. In general, the length parameter \( L \) has its first order effect on the force balance since it directly affects the mean streamline curvature and the surface area of the wake-main flow mixing surface. Both parameters do, however, have significant influence on both radius ratio and the force balance and the iteration scheme must recognize this.

After values for \( L \) and \( M \) are found which simultaneously satisfy the desired radius ratio and the axial force balance, then the desired values for flow coefficient, thrust coefficient, base pressure coefficients, etc., are calculated from the converged solution.

### Mean Streamline Shape

An exponential equation in the form of Equation 1 was selected to represent the shape of the 50% streamline. This equation can be made to have any initial radius and slope at \( Z = 0 \) and asymptotically approaches zero slope and curvature far downstream as we would expect of the real flow.
The length parameter \( L \) controls the rate at which the mean streamline radius approaches its asymptotic value of \( R_{m2} \) and, in effect, then controls the rate at which the centerbody wake washes out. It can easily be shown that \( A \) and \( B \) are determined by the desired initial radius and slope and are given by

\[
A = 1 - R_{m2} \\
B = A + L \tan \theta_{m1}
\]

if we assume an initial radius, \( R_{m1} \) of 1.

The third term in Equation 1 whose magnitude is controlled by the constant \( C \) is not needed to match the end conditions but was added to achieve a more realistic axial distribution of curvature along the mean streamline. If \( C \) is set equal to zero, the third derivative of \( R_m \) from Equation 1 is very high when \( Z \) is small. This implies a high axial gradient of mean streamline curvature and thus a high axial gradient of static pressure in the centerbody wake. Initially, it was felt that selecting \( C \) so that the third derivative of \( R_m \) would be zero at \( Z = 0 \) would result in a more realistic curvature distribution for the mean streamline. To achieve this then it can be shown that

\[
C = (-A + 3B)/6
\]

Finally, in the comparing the calculated mean streamline shapes with the model test data, it was found that a better correlation could be obtained if \( C \) was defined as

\[
C = (-A + 3B + C_9)/6
\]

where \( C_9 \) was determined experimentally and discussed in the Application of Analytical Methods Section of this report. \( C_9 \) then controls the initial value of the axial curvature gradient of the mean streamline and has the same sign.

The value of \( R_{m2} \) is indirectly based on experimental data. The Application of Analytical Methods Section of this report describes how the inner streamline radius at the downstream station was found to vary in the test program. If the inner streamline radius is known at the downstream
station, it is a relatively simple matter to calculate the mean streamline radius knowing the flow, swirl distribution, etc. and assuming zero slope and curvature at all streamlines.

**Station Calculations Normal to Mean Streamline**

**Streamline Curvatures**

In order to apply the momentum equation in the direction normal to streamlines, the streamline curvatures must be known along a potential line. Since we are assuming a shape for the mean streamline, we know only its slope and curvature and must estimate a curvature for the other streamlines. If we assume that the flow area between the mean streamline and any other streamline is approximately constant over a short distance, then we may superimpose the two cases illustrated in Figure 2. This then will approximately relate the curvature of any streamline to the mean streamline slope and curvature on the same calculation line by the following equation:

\[
\frac{1}{r} = \frac{1}{r_m} + \frac{(R_m - R)}{\cos \beta_m} \sin^2 \frac{\beta_m}{(R^2 + R_m^2 \sin \beta_m)^1.5} \quad (6)
\]

**Summary of Other Equations**

In addition to the above equation for streamline curvature, five more equations are derived in Appendix I which are required to define the main stream flow properties along a calculation line normal to the mean streamline. These additional five equations involve the six unknowns - \( r \), \( \rho T \), \( \rho \), \( T \), \( R \) and \( V_n \) and are summarized below:

\[
RV_\theta = (RV_\theta)_T - M \lambda \left( 1 - \frac{M}{2} \right) \quad (11)
\]

\[
\rho/\rho_T = \left( \frac{P}{P_T} \right) \left( \frac{T}{T_T} \right) \quad (14)
\]

\[
T/T_T = 1 + [Q V_T + (RV_\theta)/(RV_\theta)_T - (RV_\theta)^2/R^2 - V_m^2] \quad (15)
\]

\[
\frac{2R}{\rho V_m} = M \cos \beta_m \quad (16)
\]

\[
\frac{\partial V_m}{\partial \psi} = \frac{M}{2\pi \rho R} + \frac{M \lambda}{V_m} \left[ \frac{V_T}{2(RV_\theta)_T} - \frac{(RV_\theta)^2}{R^2} \right] \quad (110)
\]
Since the last two of the above equations are partial differential equations, they must be integrated along the calculation line. This was done using a second order Runge Kutta procedure and is described in more detail in the Computer Program Section of this report. The other four above equations are used as auxiliary equations in the integration procedure.

Axial Force Balance

If we remember that the outer surface of the main stream is at ambient pressure and that there is no net flow into or out of the wake region, we may write the following equation expressing equilibrium between the resultant axial pressure force and the change in axial momentum of the main stream.

\[ M \int_0^1 (V_{Z1} - V_{Z2}) \, dy = 2\pi \int_0^{R_{T1}} R(P_a - P_1) \, dR + 2\pi \int_0^{R_{T2}} R(P_a - P_2) \, dR \]  

(7)

The two terms on the right-hand side of Equation 7 may each be written as two terms, one of which represents the pressure force in the wake region and the other of which represents the pressure force in the main stream flow as follows:

\[ M \int_0^1 (V_{Z1} - V_{Z2}) \, dy = 2\pi \int_0^{R_{H1}} R(P_a - P_1) \, dR + 2\pi \int_0^{R_{T1}} R(P_a - P_1) \, dR \]

\[ + 2\pi \int_0^{R_{H2}} R(P_a - P_2) \, dR + 2\pi \int_0^{R_{T2}} R(P_a - P_2) \, dR \]  

(8)

In this analysis, the first integral on the left is calculated as follows:

\[ M \int_0^1 (V_{Z1} - V_{Z2}) \, dy = M \int_0^1 (V_{ml} \cos \theta_{ml} - V_{m2}) \, dy \]  

(9)

Where it has been assumed that

\[ \theta_1 \approx \theta_{ml} \]

and

\[ \theta_2 = 0 \]
the first integral on the right is calculated by

\[ 2\pi \int_0^{R_{H1}} R(P_a - P_1) \, dR = \pi R_{H1}^2 (P_a - P_{H1}) - C_{PL} \left[ \frac{\rho_1 RV_\theta}{H1} \right]^2 \]  

(10)

where \( C_{PL} \) is an empirical coefficient which accounts for the effect of swirl in the wake region on the hub base pressure. The third integral on the right of Equation 8 is calculated by

\[ 2\pi \int_0^{R_{H2}} R(P_a - P_2) \, dR = \pi R_{H2}^2 (P_a - P_{H2}) \]  

(11)

Collecting Equations 8, 9, 10 and 11 and rearranging gives the final axial force balance equation used in this analysis:

\[
\frac{1}{2\pi} \int_0^1 (V_m \cos \beta_m - V_m) \, dy - \int_{R_{H1}}^{R_{H2}} R(P_a - P_1) \, dR \\
- \int_{R_{H2}}^{R_{H1}} R(P_a - P_2) \, dR - \frac{1}{2} \left[ R_{H1}^2 (P_a - P_{H1}) - C_{PL} \left[ \frac{\rho_1 RV_\theta}{H1} \right]^2 \right] \\
- \frac{1}{2} R_{H2}^2 (P_a - P_{H2}) = 0
\]  

(12)

Overall Performance Calculations

After a converged solution to the flow problem is obtained, we must still calculate flow, thrust, velocity and base pressure coefficients since they are the nozzle characteristics of primary interest. To do this, the following procedure was used:

- First, a mass averaged ideal jet velocity, \( V_1 \), was calculated using total pressure and temperature at Station 1 expanding to ambient pressure. Also, a corresponding ideal density, \( \rho_1 \), was calculated.

- An ideal mass flow was calculated as

\[
\dot{M}_1 = \rho_1 A_n V_1
\]  

(13)

where \( A_n \) is the geometric annular area at the nozzle exit with no angularity factor applied.

- An ideal thrust was calculated as

\[
F_1 = \dot{M}_1 V_1
\]  

(14)
The real mass flow and thrust are taken from the converged flow solution and used to calculate flow, thrust and velocity coefficients as follows:

\[
C_F = \frac{M}{M_i} \quad (15)
\]

\[
C_T = \frac{F}{F_i} \quad (16)
\]

\[
C_V = \frac{C_T}{C_F} \quad (17)
\]

A mean total pressure at Station 1, \( \overline{P}_{T1} \), was calculated from \( V_i \) and base pressure coefficients calculated as:

\[
C_{p1} = \frac{P_{H1} - P_a}{\overline{P}_{T1} - P_a} \quad (18)
\]

\[
C_{p2} = \frac{(\overline{P}_H - P_a)}{(\overline{P}_{T1} - P_a)} \quad (19)
\]

Thus, \( C_{p1} \) is the base pressure coefficient at the outer radius of the centerbody and \( C_{p2} \) represents the average base pressure coefficient over the centerbody area. Both are based on an average nozzle exit dynamic pressure.
COMPUTER PROGRAM

General Description

The computer program was written to carry out the iterative solution to the equations presented in the previous section. Time-sharing Fortran was used. In general, input to the program consists of:

- Geometric parameters describing the nozzle exit.
- Total pressure, total temperature, and swirl distributions at the nozzle exit.
- A wake shear stress factor.
- Three empirical constants.
- An initial guess for L.
- Parameters used to calculate rotor loading coefficients if the swirl is generated by a rotor.
- Two control indicators.

All input is supplied at the time-sharing terminal at the time of program execution. Output of the program consists of:

- A general description of the flow field.
- Nozzle base pressure, flow, velocity and thrust coefficients.
- An approximate description of the rotor blade environment and loading coefficients if the swirl is generated by a rotor.

Figure 3 is a schematic block diagram of the program showing the general calculation procedure and flow of information. The solid lines show information flow between main program elements while the dotted lines show information flow between the main program and subroutines or between subroutines. Numbers in the upper left-hand corner of some blocks refer to statement numbers in the program listing given in Appendix III.

There are two options in running this program - the rotor option and the stator option. For the stator option, it is assumed that the
swirl is generated by a "no loss" stator with uniform inlet total pressure and temperature. For the rotor option, it is assumed that the swirl is generated by a rotor with uniform upstream total pressure and temperature and zero upstream swirl. The energy addition process is assumed to be isentropic but will result in a radial variation of total pressure and temperature at the nozzle exit station if a nonconstant angular momentum is specified at this station.

"ROTFLO" Subroutine

A key element of this program is the subroutine "ROTFLO" which performs the station calculations normal to the mean streamline. This subroutine uses a second order Runge Kutta method to simultaneously integrate Equations 16 and 110 along a station calculation line. Equations II, I4 and I5 are used as auxiliary equations during this integration.

"ROTFLO" can either begin with the radius given for the inner streamline and integrate outward to the tip streamline or begin with the radius given for the mean streamline and integrate both ways to the tip and hub streamlines. In either case, the initial value of the meridional velocity, $V_m$, is iterated upon until the static pressure on the tip streamline equals the ambient pressure. Twelve streamlines are used in the integration procedure and are located at 0, 4, 10, 20, 30, 40, 50, 60, 70, 80, 90 and 100 percent of the flow starting at the hub streamline. The streamlines are spaced closer together in the inner portion of the flow since the flow tends to vary more rapidly in this region.

Iteration Scheme

In order to arrive at a solution, both the mass flow rate, $M$, and the length parameter, $L$, must be iterated upon until the nozzle exit
radius ratio and axial force balance equation are satisfied. The scheme selected to do this has been called the secant method and will be briefly described for the case of two variables.

Let \( e_1 \) be the percent error in radius ratio and \( e_2 \) be the percent error in the axial force balance and plot these errors against \( M \) and \( L \) for three previous iterations as shown in Figures 4a and 4b. These points lie on error function surfaces. If we pass a plane through each of these two sets of points, we will have "secant" planes to the two error function surfaces. Suppose that in Figure 4a the secant plane intersects the \( M-L \) plane in the Line ab. Combinations of \( M \) and \( L \) which lie on Line ab can usually be expected to reduce the error \( e_1 \) to a lower value than the previous tries. Similarly points which lie along line cd in Figure 4b can be expected to reduce the error \( e_2 \). A combination of \( M \) and \( L \) then which lies on both ab and cd should then be an improved estimate for the next iteration. This then is the scheme which the subroutine "INT2" uses to give improved estimates for \( M \) and \( L \) at each step in the iteration.

In order to start the iteration procedure, initial estimates of \( M \) and \( L \) are made and then each in turn is perturbated by a small amount in order to give three starting points.

**Input Definitions**

\[
\begin{array}{ll}
R_H/R_T & \text{Nozzle exit radius ratio, dimensionless.} \\
\beta_{ml} & \text{Mean streamline angle from axial; deg.} + = \text{outward,} - = \text{inward.} \\
FF & \text{Wake mixing shear stress coefficient; based on hub streamline meridonal velocity head; dimensionless.} \\
L & \text{Initial guess for the length parameter, L, feet.} \\
C_{PL} & \text{The difference between average base pressure and hub streamline base pressure divided by hub streamline tangential velocity head; dimensionless.}
\end{array}
\]
RCUO Angular momentum, \( RV_\theta \), on tip streamline; \( \text{ft}^2/\text{sec} \).

DRCUO Angular momentum difference between hub and tip, \( (RV_\theta)_H - (RV_\theta)_T \); \( \text{ft}^2/\text{sec} \). The distribution of \( RV_\theta \) is assumed linear with stream function between hub and tip.

\( \frac{P_T}{P_a} \) Nozzle exit pressure ratio at tip; dimensionless.

\( T_{TO} \) Inlet temperature - upstream of rotor for rotor case; deg. R.

\( \text{ROT} \) 0 if swirl is generated by a stator; 1 if swirl is generated by a rotor.

\( \text{IPT} \) 1 if downstream flowfield printout is desired; 0 if not.

\( C_2 \) Ratio of downstream hub streamline radius to nozzle exit tip radius; dimensionless. (See Figure 91 for values recommended from data.)

\( C_9 \) Empirical constant determining mean streamline curvature gradient at nozzle exit station. (See Figure 92.)

The following four inputs are used only for the rotor option but must have dummy values for stator option also:

\( \sigma_T \) Rotor tip solidity; dimensionless.

\( \sigma_H \) Rotor hub solidity, dimensionless.

\( \text{VIN} \) Average rotor inlet absolute velocity; \( \text{ft}/\text{sec} \).

\( n_R \) Average rotor efficiency.

Output Definitions

Output from the program is in three blocks. The first, which is optional (depending on \( \text{IPT} \)), describes the flowfield downstream of the nozzle exit. At each axial station, it lists in this order:

\[ Z, R_m, \beta_m, c_m, R_T, R_H, V_T, V_mT, V_mH, P_H - P_a \]

The second output block is generated only for the rotor case and approximately describes the rotor blade environment, the rotor blade static pressure rise coefficient and "D" factor at each streamline.
At each streamline (starting at the hub), it lists in this order across the page:

S.L. No., R, P-Pa, $W_1$, $V_{Z1}$, U, $\sigma$, $C_{PR}$, DF

The third output block lists most of the input on the first line for reference. On the second line, it lists the overall performance parameters and other items of interest in this order:

$C_p$, $C_V$, $C_T$, $C_{PL}$, $C_{P2}$, Z, AP, L, $\dot{M}$, $F_i$

where Z is the value at the downstream Station 2 and L is the final value of the length parameter.
EXPERIMENTAL INVESTIGATIONS
TEST HARDWARE AND INSTRUMENTATION

Base Pressure Models

The base pressure model consisted of a 4 inch (10.16 centimeter) inner diameter stainless steel casing in which a 2 inch (5.08 centimeter) aluminum center body was positioned by one support strut as shown in Figure 5. To the inlet of the model, a small bellmouth was attached. Vanes to generate axial or swirling flow shown in Figure 6 were fitted behind the center body with the swirl vanes designed to produce a comparable level of swirl as observed in the full scale testing of the LF336E (Reference 1). Interchangeable inner and outer aluminum flowpaths could be positioned at the model exit plane. A total of 11 sets of different inner and outer flowpaths was designed with varying radius ratios and flow angles with a positive flow angle designated as radially outward. Table I contains pertinent data on the exit flowpath and Table II gives the contour geometry of each set. Figure 7 shows a schematic of the test model cross section.

For simplification, the model configurations will be hereafter designated by the model number as given in Table I and a prefix of either an "A" or "S" will be used to identify axial or swirling flow, respectively. Thus, S5 is the test configuration designation for Model 5 tested with swirling flow and A5 is for Model 5 with axial flow.

Test Facility

The base pressure tests were performed at the probe calibration facility at the General Electric Company, Evendale, Ohio. This test facility has the capability of adapting the probe stand for small scale model testing. With the base pressure model positioned in the test stand as shown in Figure 8, total pressure ratios of slightly greater than 1.4 and flow rates between 2-3 lbs/sec (0.9-1.4 Kg/sec) could be attained using the shop air system.

The test facility contained instrumentation systems to provide constant temperature inlet air operation for each test and provided the actuation systems for the exit plane traversing probe in immersion, yaw and pitch.
**Instrumentation**

Instrumentation on the base pressure model was kept at a minimum level with the major portion of the performance data being recorded by three port exhaust traversing probes. Eight static pressure taps were located 90° from the center body support strut and equally spaced from the inlet of which the first five were used to record wall statics for upstream flow measurements.

The three port exhaust traversing probe was mounted in a facility actuation system which had the capability of immersing, pitching and yawing the probe. For the base pressure tests, the probe was installed such that the probe static pressure ports could be nulled, i.e., probe aligned in the direction of the flow which yielded the magnitude and direction of the swirl angle. The data pressure null was indicated by a pressure balancing transducer with a null meter readout with each static pressure connected to each side.

The exhaust traversing probe was mounted aft of the model such that the axial distance could be varied to at least four model diameters downstream.
TESTING AND PROCEDURES

Test Scope

The main purpose of this test was to investigate the effects of various flow field conditions of annular jets on the base pressures of blunt bases so that experimental data could be correlated with an analytical model in order to develop a useful tool in the future design of turbotip lift fan systems. The new analytical model, including empirical constants from the tests, could then be used to predict the base pressure levels of new lift fan designs, thus reflecting permissible or nonpermissible levels of base pressure or exit geometry.

A total of 50 hours of testing was conducted consisting of three to four traverse probe axial positions with axial and swirling flows, variable pressure ratios, blockage at the exit plane to simulate louvers, and skewed swirl distributions. Table III gives a complete summary of the different configurations that were tested.

Test Procedures

Since a minimum of instrumentation was used for the tests and due to an unavailability of an adequate pressure recording system, the total and static pressures from the traversing probe and the wall statics were recorded manually from mercury manometers. Traverse data was recorded for approximately 20 radial locations from the tip to center of the base. Digital counters on the traverse probe yaw and immersion actuators were used for determination of the swirl angle and the probe radial location.

Probe Calibration

One three-port cobra probe was used to obtain a survey of the total and static pressures and the yaw (swirl) angle across the model exhaust plane. Figure 9 shows a schematic of the probe head with several pertinent dimensions.

The probe was calibrated in the probe calibration stand over a range
of pitch angles (+10° to -20°) and Mach numbers (0.6 and 0.8). The calibration was performed with the yaw angle kept constant (0°) since the actual model tests would be performed with the static pressures nulled, i.e., the probe aligned in the direction of the flow.

The recorded pressures were reduced into a coefficient form such that

\[ K_1 = \frac{P_{TO} - P_a}{P_{TP} - P_{SP}} \]

where,

- \( P_{TO} \) - plenum total pressure
- \( P_a \) - barometric pressure
- \( P_{TP} \) - total pressure indicated by probe
- \( P_{SP} \) - static pressure indicated by probe

Also, a correction factor (K2) was included due to the effect of the flow angularity (pitch), where

\[ K_2 = \frac{P_{SP}}{P_{SP} (\beta = 0^\circ)} \]

The results of the probe calibration are shown in Figure 10. These calibration characteristics provided the basis for converting the measured pressure data into the appropriate corrected pressures, where

\[ P_S = P_{TP} - (P_{TP} - P_{SP})(K_1/K_2) \]

**Data Processing**

Data reduction of the recorded parameters was done by a time-sharing computer program which calculated and integrated various flow field parameters. Further details of the procedures used for attaining overall model performance are given in Appendix II.
The results of the Base Pressure Tests are presented in the following section of this report. The discussion will be separated into major categories covering:

- Model performance with axial flow
- Model performance with swirling flow
- Model performance with variable pressure ratio
- Model performance with simulated louvers (blockage)
- Model performance with skewed swirl distribution

**Performance With Axial Flow**

Data was recorded for the axial configurations at several traverse axial distances. Figures 11 through 16 show the total and static pressure coefficient distribution for the closeup traverse position and Figures 17 and 22 show the same parameters but with the traverse plane being located 0.656 model diameters downstream. As indicated from these figures, the configurations with a positive flow angle, radially outward, exhibit a higher static pressure in the flow stream and a lower static pressure in the base region as those configurations with axial or less than axial flow angularity.

Integration of the exhaust plane at several axial distances made it possible to locate the flow streamlines in the exhaust region of the models. Figures 23 through 28 show a graphical representation of the exhaust flow fields for all the models tested with axial flow. The 100% streamline location was determined at the point where the integrated flow equalled the upstream flow with the integration starting at the centerline and proceeding radially outward. The zero percent streamline was determined at the location at which the total pressure was equal to zero. The mixing region, as indicated on the figures, is the difference between the total integrated flow and the upstream flow. In this region, the moving jet interacts with the stationary surrounding air, transfers momentum to the stationary air, thus entraining flow. Figures 29 through 31 show the amount of flow entrainment for all the models with axial flow.
Figures 32 through 34 contain the wake mixing loss characteristics for the models with axial flow with the mixing loss coefficient defined as,

\[
\omega = \frac{P_{TO} - \omega_0 (P_{TO} - P_{Sm}) - \bar{P}_T}{P_{TO} - \omega_0 (P_{TO} - P_{Sm}) - P_a}
\]

where
- $P_{TO}$ - upstream total pressure
- $P_{Sm}$ - flow section static pressure
- $\bar{P}_T$ - mass averaged total pressure
- $\omega_0$ - loss coefficient due to components of model (bellmouth, vanes, etc.)
- $P_a$ - ambient pressure

Figures 35 through 38 show the effects of model geometry on the average hub base pressure, the main flow thrust coefficient, the overall thrust coefficient and on the flow coefficient for axial flow. The calculation procedures for these parameters are discussed in Appendix II.

**Performance With Swirling Flow**

Figures 39 through 44 show the total and static pressure coefficients and swirl angle distributions for the set of models tested with swirling flow with the exhaust plane survey being made at the closeup traverse position. The same parameters for the same test conditions, but with the exhaust traverse plane being 0.656 model diameters downstream are presented in Figures 45 through 50. An immediate observation is the difference in the levels of the static pressure coefficients between configurations with axial and swirling flows. For the swirl cases, the static pressure coefficients are at least twice as low than those with axial flow.

The graphical representations of the flow fields for the models with swirling flow are shown in Figures 51 through 56. The same calculation schemes were used to establish the 100 and the zero percent streamlines and the mixing regions as with the axial cases. Figures 57 through 59 contain the flow entrainment characteristics for the configurations tested with swirling flow. Again, an immediate observation shows that the flow entrainment characteristics of the configurations with swirl are 20 to 30 percent higher than the same configurations with axial flow.
The wake mixing loss characteristics for the swirl cases are shown in Figures 60 through 62. The mixing loss coefficients are calculated in the same manner as those for the axial cases.

The effects of model geometry on the level of the average base pressure and on the base pressure at the hub outer radius are shown in Figures 63 through 65. As can be seen, swirling flow has a tremendous effect upon the levels of base pressures that were observed. Compared to the axial cases, the swirl configurations are, on an average, four to six times lower, i.e., more negative.

The effects of geometry on the main flow thrust and on the overall thrust coefficients are shown in Figures 66 and 67. Figure 68 contains the variation of the flow coefficient with model geometry.

The unstable regions as indicated in Figures 63 through 68 were observed while testing the 0.4 radius ratio models at -10 and -20 degree flow angles. Intermittent, unstable conditions existed several times with these two configurations which were signified by changes in the audible noise frequency and a fluctuation of the total and static pressures in the exhaust flow. Inserting a tool or a hand into the exhaust stream removed the instability.

Performance With Variable Pressure Ratio

The three models with zero degree flow angles were tested at two other pressure ratios, 1.2 and 1.4, with swirling flow to investigate the effects of variable pressure ratio upon the base pressures. Figures 69 through 71 show the effects of pressure ratio on the total and static pressure coefficients and on the swirl distributions. As indicated, the swirl angle and total pressure coefficients are unchanged by pressure ratio while the static pressure coefficients do show a slight change. Figures 72 and 73 show the effects of pressure ratio on the base pressure coefficients averaged over the base and at the base outer radius. The trends that are shown indicate that the average base pressure increases slightly with pressure ratio while the base pressure at the base outer radius exhibits the opposite trend.
The effects of pressure ratio upon the main flow and the overall thrust coefficients are presented in Figures 74 and 75. As shown, the thrust coefficients increase with increasing pressure ratio. Figure 76 shows that increasing pressure ratio has no significant effect upon the measured flow coefficient.

**Performance With Blockage**

The possibility that the base pressures could be increased by the addition of a blockage system, simulating exhaust louvers, was investigated. The blockage system consisted of a wooden support frame containing eight rows of 0.0645 inch (0.1638 cm) outside diameter, stainless steel tubing. The tubing spacing was selected at 0.5 inch (1.27 cm) such that a 14 percent blockage existed. The blockage system was mounted 0.5 inch (1.27 cm) aft of the nozzle exit plane. Figure 77 shows photographs of the test setup with the blockage system mounted in position.

The models with zero flow angles were tested with the blockage system installed with and without swirling flow. Figures 78 through 80 show the effects of blockage with axial flow. The only result that the blockage produced was a small increase in the flow stream static pressure of approximately 5 percent for all three configurations. The influence of the blockage upon the base pressure and the flow coefficient is insignificant as shown in Figure 81.

Figures 82 through 84 contain the effects of blockage on the total and static pressure coefficients and on the swirl angle for those models tested with swirling flow. As with the axial flow configurations, a similar trend is observed in regard to the stream static pressure, that is, a slight increase in that static pressure. Figures 85 and 86 show the influence of the blockage and the base pressures and on the flow coefficient. The blockage increased the base pressures approximately 10 percent and decreased the flow coefficient by 2 percent.
Performance With Skewed Swirl Distribution

Since the axial flow configurations exhibited a much lower level of base pressure as compared to the swirling flow cases, the possibility that a skewed swirl distribution across the flow stream would improve the base pressures was investigated.

The axial vane assembly used to produce axial flow was reworked such that a similar level of swirl as observed with the swirl vane assembly existed at the tip of the vanes. At the hub, no rework was done so that axial flow would exist there, thus intending to produce comparable levels of base pressure as observed in the axial flow cases.

Figures 87 through 89 show the total and static pressure coefficients and swirl distributions for the Models 2, 6 and 10 with zero flow angle. As shown, the levels of base pressure are between those observed for the axial and swirl cases. Table IV contains a performance comparison for Models 2, 6 and 10 with the three types of flow fields tested. These results show that for the skewed swirl distributions, base pressure, thrust and flow coefficient all increased from the observed level with complete swirling flow, the largest increase occurring in the thrust and flow coefficients.
The analytical model developed for representation of the flow around blunt bases requires an evaluation of numerous empirical constants for completion of the mathematical model. The four most significant constants are:

FF - Effective friction or loss factor representative of losses associated with the boundary between the main and wake flows.

C₂ - The area occupied by the wake flow field at axial locations far downstream of the hub base. This constant represents the ratio of the wake flow diameter to the nozzle tip diameter.

Cₚ₇ - The coefficient representative of the pressure gradients in the wake flow at the plane of the hub base. The parameter establishes the integrated average base pressure in terms of the pressures at the outer radius of the base.

C₉ - A coefficient that controls the initial rate of change of curvature of the wake flow.

The tests of the base pressure models with swirling flow provided the data necessary for evaluation of these constants. The initial step in the analysis was to determine the appropriate flow field parameters in a format compatible with the analytical model. The inlet flow to the model is represented as an average total pressure ratio, an air total temperature and the angular momentum distribution. The total pressure and temperature inputs were determined through test measurements and were assumed constant for all test models. The angular momentum in the analysis is represented by a tip momentum with a linear variation between the hub and tip. The test measurements were used to evaluate the required momentum distributions by fitting the measured profiles. The resulting variation of tip momentum and hub-to-tip momentum difference is given in Figure 90 for the range of test radius ratio. The total pressure ratio and temperature used during the analysis were 1.263 and 535° R (297° K), respectively.
Only one of the four empirical constants can be obtained directly from
the test measurements. The wake area coefficient, \( C_2 \), can be obtained by
referring to the test flow streamline distributions. Using the most down-
stream traverse location, the radius of the wake region was obtained and is
summarized in Figure 91. The wake size appears to be independent of both
model radius ratio and radial flow angle. An average value of 0.48 was
selected for the coefficient, \( C_2 \), for evaluation of the test data using the
mathematical model. A constant value of the wake size appears reasonable
for the test model since the model employed one set of turning vanes up-
stream of the contoured nozzle and exhaust plane. The swirl vane had a
hub-to-tip ratio of 0.5 with a tip radius of 4 inches (10.16 cm). Through
observations of the downstream flow profiles, it appears that all models
exhibit similar swirl and pressure distributions. Apparently, the flow
field, as established at the plane of the swirling vanes, determines the
downstream flow conditions and is not affected by the internal flowpath
of the actual test model. This consistent flow field pattern can be
expected since both axial and tangential momentum are conserved except for
friction and mixing losses.

With one of the constants established, the problem was to determine
the three remaining constants using the model test data. Through a process
of trial and error, the friction factor was established at a level of 0.04
and the values of \( C_b \) and \( C_{PL} \) were determined to be a function of radius
ratio and radial flow angle as shown in Figure 92. The justification for
these characteristics is based on agreement of predicted and measured hub
base pressure levels. A comparison of the hub base pressure coefficients
as obtained from tests and theoretical analysis is given in Figures 93
through 95.

The agreement of test and theory is fair considering the small
sampling of test configurations and the complexity of the analysis. A
comparison of test and analytically derived nozzle velocity and flow co-
efficients shows similar agreement. The agreement of velocity coefficients
is of prime importance since it includes the combined effects of swirl
distributions in addition to stream and base pressure levels. The agreement
between test and theory is within 2 percent.
The empirical constants, as derived for comparison of configurations with swirling flow, were then used to evaluate hub base pressure levels during axial flow. Without swirling flow, the value of the constant $C_2$ should be very small since the jet wake closes on itself at the hub base centerline. Likewise, the base pressure coefficient, $C_{PL}$, would be very small since the stream static pressures are uniform throughout the separated base regions. Using these assumptions, the comparison of test and analysis as shown in Figures 96 through 98 is possible. Again, the comparison shows fair agreement with the largest differences occurring for the 0.4 radius ratio configuration.

The configurations tested with the skewed swirl distribution and model "E" were compared with the analytical model using the empirical constants that were determined previously. Table V contains the comparison of test and theory. As shown, the theory predicts the test results reasonably well. This final comparison verifies the selection of the empirical constants derived from the 20 configurations previously tested and also confirms the validity of the analytical model.

Based on the comparison of test and analytical parameters such as velocity, flow and pressure coefficients, the analytical model appears to be an adequate representation of the exhaust flow downstream of annular nozzles with blunt bases. Considerable additional testing, including numerous models with variable swirl levels, along with further refinement of the analytical model, would be required to improve the levels of data correlation.
CONCLUSIONS

An analytical model was developed to predict the base pressures established by axial or swirling flow through annular jets having blunt bases. Configurations consisting of various flow angularities, radius ratios and swirl distribution can be modeled by the computer program generated from the developed theory. Over 50 hours of scale model testing were conducted to assist in the selection of several empirical constants required by the analytical model. The significant conclusions which were derived from the results of this investigation are as follows:

- Three separate factors have been recognized as major contributors to the pressure at the base of an annular nozzle, i.e., the shear forces between the high velocity main stream flow and the relatively stagnant air mass composing the centerbody wake, the meridonal curvature of the flow streamlines in the vicinity of the nozzle exit, and the radial pressure gradient due to the swirl velocity component.

- Major differences in the flowfields between axial flow and swirling flow were observed. With axial flow, base pressure coefficients of -0.2 to 0.25 were measured while with swirling flow, base pressure coefficients of -0.4 to -0.8 were not uncommon.

- Base pressure levels are unaffected by changes in pressure ratio and only slightly affected by blockage downstream of the base.

- The agreement of test and theory is fair considering the small sampling of test configurations and the complexity of the analysis. The analytical model is an adequate representation of the exhaust flow downstream of annular nozzles with blunt bases based on the comparison of test and analytical parameters.
Additional testing is required to refine the analytical model in order to improve the correlation between the theory and the test.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a_n$</td>
<td>Acceleration normal to a streamline</td>
<td>ft/sec$^2$ $($m/sec$^2$)</td>
</tr>
<tr>
<td>$A$</td>
<td>Constant, $1 - R_m^2$</td>
<td>ft $($m$)$</td>
</tr>
<tr>
<td>$A_m$</td>
<td>Model measuring section effective flow area</td>
<td>ft$^2$ $($m$^2$)</td>
</tr>
<tr>
<td>$A_n$</td>
<td>Nozzle exit annular area</td>
<td>ft$^2$ $($m$^2$)</td>
</tr>
<tr>
<td>$A_P$</td>
<td>Surface area of wake mixing zone</td>
<td>ft$^2$ $($m$^2$)</td>
</tr>
<tr>
<td>$B$</td>
<td>Constant, $A + L \tan \beta_m$</td>
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</tr>
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<td>$c_m$</td>
<td>Mean streamline curvature</td>
<td>1/ft $($l/m$)$</td>
</tr>
<tr>
<td>$C$</td>
<td>Constant, $(-A + 3B + C_9)/6$</td>
<td>ft $($m$)$</td>
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<tr>
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<td>Nozzle flow coefficient, $M/M_i$</td>
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</tr>
<tr>
<td>$C_p$</td>
<td>Specific heat at constant pressure</td>
<td>BTU/lb$^{-\circ}$R $(\text{joule/kg}^{-\circ}\text{K})$</td>
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<td>$C_{PL}$</td>
<td>Empirical coefficient $\frac{(P_H - P_{H1})}{[1/2 \rho \left(RV_0\right)^2]}$</td>
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<tr>
<td>$C_{PS}$</td>
<td>Local static pressure coefficient, $\frac{(P_S - P_a)}{(P_{T1} - P_a)}$</td>
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<tr>
<td>$C_{PT}$</td>
<td>Local total pressure coefficient, $\frac{(P_T - P_a)}{(P_{T1} - P_a)}$</td>
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<td>$C_{P1}$</td>
<td>Hub base pressure coefficient at outer radius, $\frac{(P_{H1} - P_a)}{(P_{T1} - P_a)}$</td>
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<td>Nozzle thrust coefficient, $F/F_i$</td>
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<td>$C_V$</td>
<td>Nozzle velocity coefficient, $C_T/C_F$</td>
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<td>Units</td>
</tr>
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<td>$C_2$</td>
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<td>$C_9$</td>
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<td>DF</td>
<td>Rotor diffusion factor</td>
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<td>DRCUO</td>
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<td>ft$^2$/sec (m$^2$/sec)</td>
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<td>$e_1$</td>
<td>Iteration error function in radius ratio</td>
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<td>$e_2$</td>
<td>Iteration error function in axial force balance</td>
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<td>Wake shear stress coefficient, $F_S/(1/2 \rho V_m^2)$</td>
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<td>Print control parameter, 1 if flow-field print is desired, 0 if not</td>
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<td>$J$</td>
<td>Work equivalent of heat</td>
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<td>-----------------------------------------------</td>
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<td>P</td>
<td>Static pressure</td>
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<td>Probe indicated static pressure</td>
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<td>Total or stagnation pressure</td>
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<td>Mean total pressure at nozzle exit based on ideal velocity, ( V_1 )</td>
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<td>Probe indicated total pressure</td>
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<td>Relative total pressure</td>
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<td>Dimensionless indicator (0, stator case; 1, rotor case)</td>
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<tr>
<td>r</td>
<td>Streamline radius of curvature</td>
<td>ft (m)</td>
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<td>r_m</td>
<td>Mean streamline radius of curvature</td>
<td>ft (m)</td>
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<td>Angular momentum at tip streamline, ( RV_\theta )</td>
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<td>Control parameter, 0 if swirl is generated in stator, 1 if not.</td>
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<td>R</td>
<td>Radius</td>
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<td>Mean streamline radius</td>
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<td>Tip radius</td>
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<td>Static temperature</td>
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<td>Total temperature</td>
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<td>Units</td>
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</tr>
<tr>
<td>U</td>
<td>Wheel speed</td>
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<td>Average rotor inlet absolute velocity</td>
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<td>Meridinal velocity component</td>
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<td>$V_T$</td>
<td>Total velocity component at tip</td>
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<td>$V_Z$</td>
<td>Axial velocity component</td>
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<td>$V_\theta$</td>
<td>Tangential velocity component</td>
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<td>W</td>
<td>Integrated airflow from wake centerline</td>
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<td>Rotor inlet relative velocity</td>
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<td>$W_2$</td>
<td>Rotor exit relative velocity</td>
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<td>Total integrated airflow at nozzle exit plane</td>
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<td>XIMM</td>
<td>Probe immersion</td>
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<td>Axial distance downstream of nozzle plane</td>
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<td>Streamline meridional flow angle</td>
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<td>Mean streamline meridional flow angle</td>
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<tr>
<td>$\gamma$</td>
<td>Ratio of specific heats</td>
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<td>$\delta$</td>
<td>Partial differential</td>
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<td>Tangential flow angle</td>
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<td>Angular momentum distribution factor, $-[(RV_\theta)<em>T - (RV</em>\theta)_H]/\dot{M}$</td>
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<tr>
<td>Symbol</td>
<td>Definition</td>
<td>Units</td>
</tr>
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<td>--------</td>
<td>------------</td>
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</tr>
<tr>
<td>$\rho$</td>
<td>Mass density</td>
<td>$\text{lb-sec}^2/\text{ft}^4$ ($\text{kg-sec}^2/\text{m}^4$)</td>
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<td>Ideal mass density</td>
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<td>Mass density based on stagnation conditions</td>
<td>$\text{lb-sec}^2/\text{ft}^4$ ($\text{kg-sec}^2/\text{m}^4$)</td>
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<td>$\sigma$</td>
<td>Solidity</td>
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<tr>
<td>$\psi$</td>
<td>Stream function</td>
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<td>Wake mixing loss coefficient, $\left(\frac{P_{T1} - P_T}{P_{T1} - P_a}\right)$</td>
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<td>$\omega_0$</td>
<td>Nozzle model internal loss coefficient, $\left(\frac{P_{T0} - P_T}{P_{T0} - P_{Sm}}\right)$</td>
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<tr>
<td>Subscripts</td>
<td>Definition</td>
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</tr>
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<td>------------</td>
<td>------------------------------------------------</td>
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</tr>
<tr>
<td>0</td>
<td>Upstream or reference station</td>
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<tr>
<td>1</td>
<td>Nozzle exit station, or rotor inlet station</td>
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</tr>
<tr>
<td>2</td>
<td>Downstream station, or rotor exit station</td>
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</tr>
<tr>
<td>H</td>
<td>Hub of flow field</td>
<td></td>
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<tr>
<td>m</td>
<td>Model flow or measuring station</td>
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<tr>
<td>T</td>
<td>Tip of flow field</td>
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</table>
REFERENCES


APPENDIX I

DERIVATION OF EQUATIONS OF EQUILIBRIUM NORMAL TO A STREAMLINE

Angular Momentum Distribution

It is assumed in this analysis that the angular momentum distribution is known at the nozzle exit station and that it can be adequately represented as a linear function of the stream function $\psi$ as follows:

$$RV_\theta = (RV_\theta)_T + \lambda \frac{M}{M} (1 - \psi) \quad (I1)$$

where

$$\lambda = - \frac{[(RV_\theta)_T - (RV_\theta)_H]}{M} \quad (I2)$$

Assuming that angular momentum is conserved along any streamline, the above two equations can be applied at any point downstream of the nozzle exit station as well.

Pressure-Temperature-Density Relations

Assuming uniform stagnation pressure and temperature at the upstream Station 0 and an isentropic process between Station 0 and the nozzle exit Station 1, we write

$$P_1 = P_{TO}\left(\frac{T_1}{T_{TO}}\right)^{\gamma/(\gamma-1)}$$

which will apply to all streamlines at Station 1. Further, if we know the stagnation pressure loss between Station 1 and any downstream station, we may write

$$\frac{P}{P_{TO}} = \left(\frac{P_T}{P_{T1}}\right)\left(\frac{T}{T_{TO}}\right)^{\gamma/(\gamma-1)} \quad (I3)$$

which will apply to any point downstream of the nozzle exit. Similarly, we may write for the density:

$$\frac{\rho}{\rho_{TO}} = \left(\frac{P_T}{P_{T1}}\right)\left(\frac{T}{T_{TO}}\right)^{1/(\gamma-1)} \quad (I4)$$

Notice that the above three equations apply even though there may be energy addition (as by a fan rotor) between Stations 0 and 1 as long as the process is isentropic.
Energy Relations

Case 1:

If no energy is added between Stations 0 and 1, then conservation of energy along a streamline results in

\[ \frac{T}{T_{T0}} = 1 - \left( V_\theta^2 + V_m^2 \right) / \left( 2g J C_p T_{T0} \right) \]

Case 2:

If the angular momentum at the nozzle exit is entirely the result of isentropic energy addition by a fan rotor, then conservation of energy along a streamline results in

\[ \frac{T}{T_{T0}} = 1 + \left( V_{T1}^2 \frac{(R V_\theta / (R V_\theta)_T)}{(R V_\theta)_T} - V_\theta^2 - V_m^2 \right) / \left( 2g J C_p T_{T0} \right) \]

where the energy added at the rotor tip is

\[ \Delta T_T = V_T^2 / \left( 2g J C_p \right) \]

We may combine the above two cases into one equation

\[ \frac{T}{T_{T0}} = 1 + \left( [Q V_{T1}^2 \frac{(R V_\theta / (R V_\theta)_T)}{(R V_\theta)_T} - V_\theta^2 - V_m^2 \right) / \left( 2g J C_p T_{T0} \right) \]

by defining

\[ Q = 0 \text{ for no energy addition (stator case)} \]
\[ Q = 1 \text{ for rotor energy addition (rotor case)} \]

Since \( V_\theta = R V_\theta / R \) the above equation may be written as

\[ \frac{T}{T_0} = 1 + \left( [Q V_{T1}^2 \frac{(R V_\theta / (R V_\theta)_T)}{(R V_\theta)_T} - \frac{(R V_\theta)_T^2}{R^2} - V_m^2 \right) / \left( 2g J C_p T_{T0} \right) \]

Continuity

By noting that

\[ dR = -dn \cos \theta_m \]

we may express the continuity equation along any stream tube as follows:

\[ dV = 2\pi R \rho V_m dR / M \cos \theta_m \]

or

\[ \frac{\partial R}{\partial V} = \frac{M \cos \theta_m}{2\pi \rho V_m R} \]

\[ (16) \]
Momentum Normal to a Streamline

The acceleration normal to a streamline of an element of fluid is given by

\[ a_n = \frac{V_m^2}{r} - V_\theta^2 \cos \beta_m/R \]

The mass of this element is given by

\[ dm = \rho R d\theta dS dn \]

The normal pressure force which balances the momentum force is given by

\[ dF = R d\theta dS dP \]

Then since

\[ dF = a_n dm \]

we may combine the above three equations to write

\[ \frac{\partial P}{\partial n} = \rho \left( \frac{V_m^2}{r} - V_\theta^2 \cos \beta_m/R \right) \]

The derivative of stream function may be expressed as

\[ \frac{\partial y}{\partial n} = -2\pi R \rho \frac{V_m}{M} \]

and the last two equations may be continued to yield

\[ \frac{\partial P}{\partial y} = \frac{(V_\theta^2 \cos \beta_m/R - V_m^2/R)/(2\pi R V_m)}{V_\theta^2 \cos \beta_m/R - V_m^2/R} \]  

This equation gives the pressure gradient normal to a streamline required to balance the momentum forces normal to the streamline.

Combined Equation

Equations 11 through 17 can be combined to eliminate pressure as a variable in Equation 17 and yield a new form for the momentum equation. This will then eliminate the need for Equation 13 in subsequent calculations. First, we differentiate Equation 13 with respect to the stream function to get

\[ \frac{\partial P}{\partial y} = \frac{V}{\gamma-1} \rho TO \left( \frac{P}{P_{TL}} \right)^{\gamma/(\gamma-1)} \frac{\partial (T/TO)}{\partial y} \]
where we have assumed that the total pressure loss factor is constant in a direction normal to the streamlines so that $\frac{\partial (P_T/P_{TI})}{\partial \gamma} = 0$. Using the perfect gas equation of state and Equation 14 in the above result gives:

$$\frac{\partial P}{\partial \gamma} = \frac{g J C_p \rho T_{TO} \frac{\partial (T/T_{TO})}{\partial \gamma}}{(R V_T T)}$$

(18)

Next, we differentiate Equation 15 with respect to stream function and use Equation 11 in the result to get

$$\frac{\partial (T/T_{TO})}{\partial \gamma} = \left[ \frac{V_{T1}^2 M \lambda Q}{(RV_{G})_T} - \frac{2R (RV_{G}) M \lambda - (RV_{G})^2 \frac{\partial R}{\partial \gamma}}{R^2} - \frac{2 V_m \frac{\partial V_m}{\partial \gamma}}{R^3} \right]$$

(2g J C_p T_{TO})

Using Equation 19 in Equation 18 to eliminate the temperature derivative and then replacing the left-hand side of Equation 17 with the result gives

$$\rho \left[ \frac{V_{T1}^2 M \lambda Q}{(RV_{G})_T} - \frac{2R (RV_{G}) M \lambda - (RV_{G})^2 \frac{\partial R}{\partial \gamma}}{R^3} - \frac{2 V_m \frac{\partial V_m}{\partial \gamma}}{R^3} \right] =$$

$$\frac{V_\theta^2 \cos \beta_m / R - V_m^2 / r}{\pi R V_m}$$

Use of Equation 16 in the above and then solving for $\frac{\partial V_m}{\partial \gamma}$ finally gives a new form of the momentum equation as follows:

$$\frac{\partial V_m}{\partial \gamma} = \frac{\lambda}{2\pi \rho R R} + \frac{\lambda}{V_m} \left[ \frac{V_{T1}^2 Q}{(RV_{G})_T} - (RV_{G}) \right]$$

(110)

This equation gives the meridional velocity gradient required to balance the momentum forces normal to a streamline.
APPENDIX II

DATA ANALYSIS PROCEDURES

The exhaust flow of the various models was surveyed by radial traverses using the 3 element probe. The flow surveys for the various configurations consisted of approximately 20 discrete data points approximately 0.1 inch (0.254 centimeters) apart. The outer radial traverse boundary was established at the location where the total pressure was just equal to zero. The inner radial boundary was selected on the centerline of the particular model being surveyed.

The following discussion presents the calculation procedures used for analysis of the exhaust probe data. The calculations were performed using a time-sharing computer program.

The following data obtained from the exhaust probe was used as input to the data reduction program:

- XIMM, Probe Immersion
- $P_T$, Total Pressure (corrected for probe calibration)
- $P_S$, Static Pressure (corrected for probe calibration)
- $\alpha$, Yaw (Swirl) Angle

Additional fixed data input based on average conditions during the complete traverse cycle where:

- $T_{TO}$, Total or Plenum Temperature
- $P_a$, Barometric Pressure
- $P_{Sm}$, Model Flow Section Static Pressure
- $\beta$, Model Flow Angle
- $P_{TO}$, Upstream or Plenum Total Pressure

Several overall performance parameters were initially calculated as follows:

- Flow Section Mach Number, $M_m = \left[ \frac{2}{\gamma-1} \right]^{1/2} \left( \frac{P_{TO}}{P_{Sm}} \right)^{\gamma-1}
- Flow Section Static Temperature, $T_{Sm} = T_T / (1 - \frac{\gamma-1}{\gamma} M_m^2)$
- Flow Section Velocity, $V_m = M_m (\gamma g R T_{Sm})^{1/2}$
Flow Section Density, \( \rho_m = \frac{P_{Sm}}{g R T_{Sm}} \)

Mass Flow, \( M = \rho_m V_m A_m \)

Nozzle Exit Total Pressure, \( \bar{P}_{T1} = P_{T0} - \omega_0 (P_{T0} - P_{Sm}) \)

Ideal Mach Number, \( M_i = \left[ \left( \frac{2}{\gamma-1} \right) \left( \frac{\bar{P}_{T1}}{P_a} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{1/2} \)

Static Temperature, \( T_S = T_{TO}/(1 + \frac{\gamma-1}{2} M_i^2) \)

Ideal Velocity, \( V_i = M_i (\gamma g P_T) \)

Ideal Mass Flow, \( M_i = (P_a g R T_S V_i) \)

Ideal Thrust, \( F_i = M_i / V_i \)

At each discrete point or immersion, the following parameters were calculated:

Absolute Mach Number, \( M = \left[ \frac{2}{\gamma-1} \left( \frac{P_T}{P_S} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]^{1/2} \)

Total Pressure Coefficient, \( CPT = (P_T - P_a)/(\bar{P}_{T1} - P_a) \)

Static Pressure Coefficient, \( CPS = (P_S - P_a)/(\bar{P}_{T1} - P_a) \)

Static Temperature, \( T = T_T/(1 + \frac{\gamma-1}{2} M^2) \)

Absolute Velocity, \( V = M(\gamma g R T) \)

Flow Per Unit Area, \( W/A = (P_a/RT) V \cos \alpha \cos \beta \)

Thrust Per Unit Area, \( F/A = W/A V \cos \alpha \cos \beta + (P_S - P_a) \)

The total model exhaust flow was integrated to obtain the following performance:

Airflow, \( W = \Sigma (W/A) \Delta A \)

Total Thrust, \( F = \Sigma (F/A) \Delta A \)

Mass Average Total Pressure, \( \bar{P}_{T1} = (\Sigma P_T (W/A) \Delta A)/W \)

Hub Base Pressure, \( \bar{P}_H = \Sigma (P_{SB}) \Delta A/A \)

The following overall performance parameters were then calculated:

Flow Coefficient, \( C_F = M_i/M \)

Thrust Coefficient, \( C_T = F/F_i \)
Base Pressure Coefficient at Hub Exit Radius, \( C_{P1} = \frac{P_{H1} - P_a}{P_{T1} - P_a} \)

Average Base Pressure Coefficient Across Base, \( C_{P2} = \frac{\bar{P}_H - P_a}{P_{T1} - P_a} \)

The flow streamline locations were determined as follows: During the flow integration, the radius and the resulting integrated flow were stored in an array throughout the entire flow stream; then, for 10 to 100 percent flow, the appropriate radius was determined from the stored data by linear interpolation.
APPENDIX III

COMPUTER PROGRAM LISTING

*#RUNH  *;HBASE(NOGO,CORE=30)
100 COMMON PRACTO,PAM,ROTO,PLOSS,ROH1,ROCU,PI,ROG0,V0,P0,MF,RCU0,LAM
110&   G1,G2,C3,C4,PTINT,DMF,TO,RO1,SOL1,SOLH,IND,VIN,EFF
120 REAL LAM,MF,DMF(11),MF1,L,RP(4),RO(4),ZIP(4),ZOP(4),BMP(4),ZMP(4)
130 INTEGER ROT
140 DIMENSION RPP(4),X(3),Y(3),VI(12),V12(12),EI(3),E2(3),RCU(12),
150&   PRACTO(12),R(12)
160 I PRINT 100 ; PRINT 100
170 PRINT, R/R,BC,FL,CL,RCU0,DCRU0 *; READ,RR,BO,FF,L,CPL,RCU0,DCRU0
180 IF(GR.ER.0.0) GO TO 399
190 IF(R.ER.0.) PRINT, F/P,TIN,ROT,PI,2,2,9,9,10,SOL1,SOLH,IN,EFF
200 REAL GA,5427.12745;IND=0
210 GAM=1.4 ; G2=1/(GAM-1)
211 TO=1/TIN*(1+(V0**(1/G2)-1)*(1/EFF-1)*ROT)
212 RG=63.355 ; XI=778.167 ; C3=2*G*G1*G1+G0*G0
215 V0=SQRT(C3*(V0**(1/G2)-1)*TIN/T0)
220 ROTO=0
230 IF(RCU0.NE.0.) ROTO=ROT/RCU0
240 C4=V0**2*5.R0TO
250 PAM=14,696*144
260 P0=PAM
270 IF(ROT.EQ.0) P0=PAM*(1-V0**2/C3)**(1-G2)
280 RH00=P0/G/RG/T0
290 PI=3.14159 ; B0=BO*PI/180
310 ITR=1 ; MAXIT=10
320 C1=P1*(1-RR**2)/(1+RR**2)
322 VMAV=V0**2-RCU0**2*(1-RR**2)/2.5
324 TRATIO=1+(V0**2*(RCU0+5*DCRU0)+ROT-(RCU0+5*DCRU0)**2-VMAV**2)/C3
326 RH0=RH00+TRATIO*C2
330 MF=2*Cl*RH0+VMAVCOS(B0)
335 MF=.9*MF
340 RK=RK*(2/(1+RR**2))**.5
350 R2=C2*(2/(1+RR**2))**.5 ; RM2=1
360 V2=V0**2;V0
370 DO 4 L=1,12
380 RCU(L)=RCU0+DCRU0*(12-L)/10
385 RCU(L)=RCU0+DCRU0 ; RCU2=RCU0+.96*DCRU0
390 PRACTO(L)=(1+V0**2*RCU0/(RCU0/C3)**G1*P0/PAM
400 4 CONTINUE
410 Z=2
414 PLOSS=(1-V2**2/(C3+V0**2*ROT))**(1-G1)/PRACTO(12)
430 9 CALL ROTFLO(1,RHU,8,0,RT2,RH2,V2,FP2,FM2)
450 A=1-RM2
500 B=A+ATAN(B0)
505 C=-(A+3*B+C9)/6
510 I=1 ; DZM=Z/10 ; Z=0
520 V2=V0 ; AP=0 ; FFZ=0 ; PFZ=0 ; PLOSS=1 ; IT=0
525 BMX=ABS(B0)
530 10 EP=EXP(-Z/L)
540 RM=2B+Z/L;C+(Z/L/L)*EP+RM2
550 RMP=-(C-B+Z/L/C+Z/L/L)*EP/L
560 RMP=R2-2B+2C+Z/L/C+Z/L/L)*EP/L
570 B-reply=ATAN(RMP)
575 IF(ABS(BH)>65*BMX) BMX=ABS(BH)

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APPENDIX III (cont'd)

580 CM=RMPP/(1+RMPP*2)**1.5
590 CALL ROTFL05(RM,BN,CM,RT,RH,V2,VMT,VMH,PH)
600 IF(ABS((RM2-RM)/(RM2-1))>0.0) OR (ABS(BM).GT.2*BMAX))
602 GO TO 13
610 IF(IG.EQ.1) GO TO 13
620 Z=Z-DZ*(ABS(1-RM2)*ABS(RM2-RM)/(RML-RM2-RM)/(RML-RM))
630 IT=1
640 GO TO 10
650 13 IF(IPT+IHD.EQ.2) PRINT 2,Z,RH,BM*180/PI,CM,RT,RK,V2,VMT,VMH,PH-PAM
670 ZH=Z+(RM-RH)*S1N(BH)
680 ZT=Z-(RT-RM)*S1N(BM)
690 IF(I.EQ.1) GO TO 12
700 BH=ATAN((RH-RHL)/(ZH-ZHL))
710 DAP=PI*(RH+RHL)*(Z11-ZHL)/COS(BH)
720 AP=AP+DAP
730 DFF=.5+RHOI*F*DAP*(VMH*2+VMHL*2)/2
740 PLOSS=PLOSS+((1-DFF)*PIINT)
750 V2=((C3+UO*2*ROI)+(C3+U0*(ROI+10)**(-1/GI))**.5
760 FFZ=FFZ+DFF*C0S(BH)
770 PFZ=PFZ+((PH+PHL)/2-PAM)*DAP*SIN(BH)
780 IF((IT.EQ.1) OR (I.GT.50)) GO TO 20
800 12 RHL=RH ; RML=R-M ; ZHL=ZH ; VMHL=VMH ; PHL=PH
810 IF(I.EQ.3) GO TO 15
820 RIP(I)=RHL ; ROP(I)=RT ; ZIP(I)=ZHL ; ZOP(I)=ZT ; ZMP(I)=Z
830 RPP(I)=RM
840 15 I=I+1 ; Z=Z+DZ
850 GO TO 10
860 20 ZIP(4)=0 ; ZOP(4)=0
880 CALL INT(RIP,ZIP)
890 CALL INT(ROP,ZOP)
900 RR=RIP(4)/ROP(4)
910 CALL INT(RMP,ZIP)
920 CALL INT(RPP,ZIP)
930 RHI=RIP(4) ; RM1=RPP(4) ; ZM1=ZMP(4)
950 EP=EXP(-ZM1/L)
960 RMPP=(A-B+(B-2*C)*ZM1/L+C*ZM1/L/L)*EP/L
970 RMP=(A-2*B+2*C*B-4*C)*ZM1/L+C*ZM1/L/L)*EP/L/L
980 BM=ATAN(RMP)
990 CM1=RMPP/(1+RMPP*2)**1.5
1000 CALL ROTFL05(2,RM1,BM1,CM1,RT1,RH1,V0,FP1,FPH1,FM1)
1010 CALL ROTFL05(1,RM2,0.,0.,RT2,RH2,V2,FP2,FPH2,FM2)
1020 1030 ERR1=(CRIIT-RR)/RR
1040 FPHX=C1*BPHX
1050 ERR2=(FP2+FPH2-FM2-FP2+FPHX-FPH1+FM1-FPHX)/FM1
1060 IF((ABS(ERR1).LT.003) AND (ABS(ERR2).LT.003))
1061 OR (IPT.EQ.9)) GO TO 30
1065 IF((ABS(ERR1).LT.003) AND (ABS(ERR2).LT.003)) IND=1
1070 IF(IND.EQ.MAXIT) GO TO 26
1080 23 DO 40 I=1,2
1090 X4(I)=X3(I)
1100 Y4(I)=Y3(I)
El(4-I) = El(3-1)
E2(4-I) = E2(3-I)

X(I) = MF ; Y(I) = L ; El(I) = ERR1 ; E2(I) = ERR2

IF(I = 1) GO TO 41 ; IF(I = 2) GO TO 42

CALL INT2(X,Y,El,E2,MF,L)

IF (ITR = 1) GO TO 41
IF (ITR = 2) GO TO 42

CALL INT2(X,Y,El,E2,MF,L)

43 PRINT X(1), Y(1), ERR1, ERR2

ITR = ITR + 1 ; LAM = DRCU0/MF

IF (IND = 1) PRINT 100

GO TO 23

41 L = L(1 - .05*ABS(ERR2)/ERR2) ; GO TO 43

42 tF = MF < (I+iR2)/(1+RR^2)/(1-RRTA2)*(1+RR*R2) ; GO TO 45

26 PRINT "ADDITIONAL ITERATIONS" ; READ NIT

IF (NIT = 0) GO TO 30

MAXIT = MAXIT + NIT ; GO TO 23

30 MFI = 0 ; FI = 0

31 NHO1 = RH00*(PAM/P0)"(1/GAM)

32 DO 36 I = 1, 12

33 VI2(I) = C3(I-I)*PRATI(I)"(-1/G1)*(PRATI(I)"(ROT/G1))

34 VI(I) = VI2(I)".5

35 CONTINUE

36 MFI = FI * NHO1 * (RIP(4)*RIP(4) - RIP(4)*RIP(4) + C6/*10

37 FI = MFI * C6/10

38 CF = MF/MFI

39 CT = (FPH2-FPH2-FPH2)/FI

40 CV = CT/CF

41 VIB2 = (FI/MFI)"2

42 CS = C5 + V0"2*RCU0(R0)*RTO

43 DELPT = [1-VIB2/C5]"(-1)*PAM

44 CPL = FPH1/DELPT/PI/RH1"2

45 CP2 = CP1*(FPH1+FPH2)/FPH1

46 PRINT 100

47 PRINT , RR, B0, FF, CPL, RCU0, DRCU0

48 & VI T0 ROT ITR

49 PRINT 102, RR, B0*100/PI, FF, CPL, RCU0, DRCU0, C6/10, T0, ROT, ITR

50 PRINT 100

51 PRINT , CF, CV, CT, CP1, CP2, Z, AP, L, MF, FI

52 PRINT 105, CF, CV, CT, CP1, CP2, Z, AP, L, MF, FI

53 GO TO 1

54 STOP ; END

103 FORMAT (1H )

104 FORMAT (1H "AFTER", I2, " ITERATIONS ERR1 = ", F6.3, " ERR2 = ", F6.3)

105 FORMAT (1H , F7.3, F7.1, F6.4, F7.3, F7.3, F7.3, F7.2, F7.0)

106 FORMAT (1H , F7.3, F7.1, F6.4, F7.3, F7.3, F7.2, F7.0)

107 FORMAT (1H , 999 STOP ; END

108 FORMAT (1H , 1600 SUBROUTINE INT(R, Z)

1620 DIMENSION R(4), Z(4)

1630 C5 = (R3-R1)/(Z1-Z1) - (R2-R1)/(Z2-Z1)/(Z3-Z1)/(Z3-Z1)

1640 C2 = (R2-R1)/(Z2-Z1) - C5*(Z2+Z1)
APPENDIX III (cont'd)

1640  CI = R(1)-C2+Z(1)-C3*Z(1)**2
1650  RC(4) = CI+C2*Z(4)+C3*Z(4)**2
1660  RETURN ; END
1670*
1680  SUBROUTINE ROTFLO(R,RMB3$CM,RZTRH DV2,PR1,PR2,PR3)
1690  COMMON PRATIO,FAM,ROT,OLOS,RH01,RCU,P1,RH02,V0,P0,MF,RCU0,LAM
1700& G1,C3,C4,P1MT,DMF,T0,ROT,SOL,IND,W1,EFF
1710  REAL LAM,VM(12),R(12),P(12),RCU(12),PRATIO(12),MF,DMF(11),VX(12)
1712  INTEGER ROT
1715  DATA VX(1,1,1,1,1,1,1,1,1,1,1,1,1,1,1,1)
1720  KS = 7 ; PLOS = POLQ
1730  IF(NP.EQ.1) KS = 1
1735  IF(NP.EQ.2) PLOS = 1.0
1740  K = 0 ; PR1 = 0 ; PR2 = 0
1742  DO 10 I = 1,11
1744  3 DMF(I) = 0*MF
1745  3 DMF(C) = 0*MF
1746  VM(KS) = V2 ; R(1) = RH ; R(7) = RH
1748  IF(ABS(CM).LT.2E-16) CM = 2.E-18
1750  DO 10 I = 1,KS
1752  TRATIO = 1+((V0**2+RCU(I))*ROTO-(RCU(I)/R(1))**2*VM(I)**2)/C3
1755  RH0 = RH00*TRATIO*G2*PLOS
1758  F1 = 1/CH(RH-R(I))/COS(BM)
1760  F2 = SIN(BM)**2 ; F3 = K(I)**2-RM**2
1762  F4 = R(I)**2+(RM*SIGN(BM))**2
1764  CV = F1+F2+F3+F4**1.5 ; IF(ABS(CV).LT.2E-18) CV = 2E-18
1766  F5 = CV/2/F4/RH0/R(I)
1768  F6 = LAM/VM(I)*(RCU(I)/R(I)**2-C4)
1770  DVMI = F5*F6
1772  DRH = VM(R)/VM(I)/R(I)*COS(BM)
1774  DTRATIO = (-4*LAM+RCU(I))R(I)**2-(LAM+RCU(I))/R(I)*DRH-VM(I)*DVM)
1776  2/C3
1780  DRHO = DMF(I)*DTRATIO/1TRATIO
1790  DCV = (DR1/COS(D1))/F1**2-2*R(I)*DR1+F2/F4**1.5*(1-1.5*F3/F4))/CV
1792  DRSQ = DR1*2*R(I)
1794  DRSQ = DRSQ-(DRHO+DVMI/VM(I))
1796  DDVM = -F5*(DRHO-DRI/R(I)-DCV)=-F6*DVMI/VM(I)
1798& = -LAM/VM(I)/(R/K)**2*(LAM**2+RCU(I))DR1/R(I)
1800  2000  DDMQ = -LAM/VM(I)/(R/K)**2*(LAM**2+RCU(I))DR1/R(I))
1802  VM(I) = VM(I)**2-(DVMI+DMF)**1/2)*DMF(I)**.5
1804  TRATIO = 1+CV2*RCU(I+1)*ROTO-(RCU(I+1)/R(I)**2-VM(I)**2)/C3
1806  RH0 = RH00 TRATIO*G2*PLOD
1808& CV1 = 1/(CH+(RN-R(I))/COS(BM))+(R**2+R**2)*SIGN(BM)**2/2
1810 & (R**2+R**2)*SIGN(BM)**2)**1.5
1812  DVM2 = CV2/2/RH0/R(I)+LAM/VM(I)*(RCU(I+1)/R(I)**2-C4)
1814  DRI = 5/PI/RH0/R(I)*COS(BM)
1816  VM(I+1) = VM(I)+DVM1+DVM2)**1/2*DMF(I)/2
1818  R(I+1) = R(I)+(DR1+DRI)**2*DMF(I)/2
1820  CONTINUE
1822
1824 & CONTINUE
1826  2800  IF(K.GT.20) GO TO 32
2000  IF(K.GT.20) GO TO 32
2100  IF(ABS(1-V21/V2).LT.00001) GO TO 18

-49-
APPENDIX III (cont'd)

2110 IF(KR.EQ.1) GO TO 15
2120 VM(KS)=.95*VI(KS)
2130 GO TO 5
2140 15 VM(KS)=VMIT+(VMIT-VMTI)/(V21-V22)*(V21-V22)
2150 DEC=VM(KS)/VMIT-1
2160 IF(ABS(DEC).GT.2) VM(KS)=VMIT*(1+.2*DEC/ABS(DEC))
2165 IF(KR.EQ.1) RM=RM1-(RM2-RM1)/(VM21-VMIT)*(VMIT-VM(1))
2170 GO TO 5
2180
2190 18 IF(KR.EQ.1) GO TO 21
2200* DO 20 J=1,6
2220 I=J
2230 TRATIO=1+(V0**2*RCU(I)+ROT0-(RCU(I)/R(I))**2-VM(I)**2)/C3
2240 RHO=RHO0*TRATIO**2*PLOS
2250 F1=1/M+C*M/R(I)/COS(BM)
2260 F2=1/SIN(BM)**2 ; F3=R(I)**2-R(I)**2
2270 F4=R(I)**2+R(I)**2*R(SIN(BM))**2
2280 CV1=1/F1+F2+F3/F4**1.5 ; IF(ABS(CV1).LT.2.E-18) CV1=2.E-18
2290 F3=CV2/P1/RHO/R(I)
2300 F6=1/VM(VM1)*RCU(I)/R(I)**2-C4
2310 DVM=1+F5+F6
2320 DR1=.5/P1/RHO/VM(I)/R(I)**2*SIN(BM)
2330 DTRATIO=C4*(LAN+RCU(I)/R(I)**2-VM(I)/DVM1)*RHO**2/C3
2340 D1=0*TRATIO/DTRATIO
2350 DDCS=DCS*(DCS/RHO+DVM1/VM(I))
2360 DVM=-F5*(D1+D1+D1**2)*F6*+DVM1/VM(I)
2370 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2380 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2390 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2400 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2410 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2420 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2430 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2440 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2450 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2460 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2470 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2480 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2490 D12=LAN**2/(LAN+LAN**2)**2*LAN**2**2/(LAN+LAN**2)**2
2500 20 CONTINUE
2510* IF(KR.EQ.2) GO TO 21
2530* RT=R(I); RM=R(I); PM=VM(I); PR2=VM(I)
2540 TRATIO=1+(V0**2*RCU(I)+ROT0-(RCU(I)/R(I))**2-VM(I)**2)/C3
2550 PR3=PM*TRATIO**2*PLOS
2560 RHO=RHO0*TRATIO**2*PLOS
2570 PM=0
2580 DO 22 I=1,11
2590 PM=PM+TRATIO(I)+TRATIO(I+1)/2*(R(I+1)**2-R(I)**2)
2610 22 CONTINUE
2510* PM=PM*PAM*PLOS*PI
2630 GO TO 35
APPENDIX III (cont'd)

2640 21 DO 25 I=1,12
2650 TRATIO=1+(VO^2*RCU(I)^2)*ROTO-(RCU(I)/R(I))^2-VM(I)^2)/C3
2670 IF(I.EQ.1)RHO=RHO0*TRATIO^G.*PLOS
2690 CONTINUE
2700 END

2740 30 CONTINUE
2750 PR2=P1*V0^2*(PAM-P(I))
2770 32 PRINT 33,K1,VM(K1),VM(12),R(K1),R(12)
2775 GO TO 35
2780 PRINT 33, "ROTFLO2 NOT CONVERGED K=26",11,2F7.1,2F7.3)
2785 PRINT 38
2790 DO 37 I=1,12
2800 VI=VX(I)*VIN
2810 DTI=(V0^2*V0^2/C3*T0)
2815 TSI=T0-DTI=VI^2/C3*T0
2820 D1=DI(2)-DI(3)-C1(3)*C2(3)
2830 D2=D1(3)*C2(1)-C1(1)*C2(3)
2840 D3=D1(1)*C2(2)-C1(2)*C2(1)
2850 DF1=1 ; DF2=1
2860 MF-X(I)+DF1*(D1/D3-X(I))
2870 LF-Y(I)+DF2*(D2/D3-Y(I))
2880 DEL1=MF/X(I) ; DEL2=1-L/Y(I)
2890 RETURN ; END

SUBROUTINE INT2(X,Y,E1,E2,MF,L)
REAL MF,L
DIMENSION X(3),Y(3),E1(3),E2(3)
DIMENSION C1(3),C2(3)
CALL COEFDX(Y,E1,E1)
CALL COEFDX(Y,E2,E2)
D1=C1(2)+C3(3)-C1(3)*C2(2)
D2=C1(3)*C2(1)-C1(1)*C2(3)
D3=C1(1)*C2(2)-C1(2)*C2(1)
DF1=1 ; DF2=1
MF-X(I)+DF1*(D1/D3-X(I))
LF-Y(I)+DF2*(D2/D3-Y(I))
DEL1=MF/X(I) ; DEL2=1-L/Y(I)
RETURN ; END

REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.
APPENDIX III (concluded)

3070 SUBROUTINE COEF(X,Y,E,C)
3080 DIMENSION X(3),Y(3),E(3)
3090 DIMENSION C(3)
3100 D1=X(1)*Y(2)+X(2)*Y(3)+X(3)*Y(1)-X(3)*Y(2)-X(2)*Y(1)-X(1)*Y(3)
3110 D2=E(1)*Y(2)+E(2)*Y(3)+E(3)*Y(1)-E(3)*Y(2)-E(2)*Y(1)-E(1)*Y(3)
3120 D3=X(1)*E(2)+X(2)*E(3)+X(3)*E(1)-X(3)*E(2)-X(2)*E(1)-X(1)*E(3)
3130 D4=X(1)*E(2)+E(2)*Y(3)+E(3)*Y(1)+E(3)*Y(2)+E(2)*Y(1)+E(1)*Y(3)
3140 C(1)=D1/D4
3150 C(2)=D2/D4
3160 C(3)=D3/D4
3170 RETURN ; END
3180 FUNCTION TAN(XXX);TAN=SIN(XXX)/COS(XXX); RETURN ; END
**TABLE I**

**Base Pressure Model Descriptions**

<table>
<thead>
<tr>
<th>Model</th>
<th>R/RT</th>
<th>Flow* Angle</th>
<th>Outer Flowpath Exit Diameter (In. (Cm))</th>
<th>Inner Flowpath Exit Diameter (In. (Cm))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4</td>
<td>10</td>
<td>3.116 7.915</td>
<td>1.246 3.165</td>
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<tr>
<td>2</td>
<td>0.4</td>
<td>0</td>
<td>3.116 7.915</td>
<td>1.246 3.165</td>
</tr>
<tr>
<td>3</td>
<td>0.4</td>
<td>-10</td>
<td>3.116 7.915</td>
<td>1.246 3.165</td>
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<td>4</td>
<td>0.4</td>
<td>-20</td>
<td>3.116 7.915</td>
<td>1.246 3.165</td>
</tr>
<tr>
<td>5</td>
<td>0.55</td>
<td>10</td>
<td>3.420 8.687</td>
<td>1.879 4.773</td>
</tr>
<tr>
<td>6</td>
<td>0.55</td>
<td>0</td>
<td>3.420 8.687</td>
<td>1.880 4.773</td>
</tr>
<tr>
<td>7</td>
<td>0.55</td>
<td>-10</td>
<td>3.420 8.687</td>
<td>1.878 4.773</td>
</tr>
<tr>
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<td>-20</td>
<td>3.420 8.687</td>
<td>1.879 4.773</td>
</tr>
<tr>
<td>9</td>
<td>0.70</td>
<td>10</td>
<td>4.000 10.160</td>
<td>2.795 7.099</td>
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<tr>
<td>10</td>
<td>0.70</td>
<td>0</td>
<td>4.000 10.160</td>
<td>2.803 7.099</td>
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<tr>
<td><strong>E</strong></td>
<td>0.638</td>
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<td>3.710 8.052</td>
<td>2.366 6.010</td>
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* Radially out designated positive angle
** Scaled from LF336/E lift fan (see Reference 2)
### TABLE II

Inner and Outer Exit Contour Geometries of the Base Pressure Models

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<th>MODEL:</th>
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<th>4</th>
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<tbody>
<tr>
<td>Z/RT</td>
<td>(R/RT)_H</td>
<td>(R/RT)_T</td>
<td>(R/RT)_H</td>
<td>(R/RT)_T</td>
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<tr>
<td>0</td>
<td>0.400</td>
<td>1.000</td>
<td>0.400</td>
<td>1.000</td>
</tr>
<tr>
<td>-0.128</td>
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<td>0.983</td>
<td>0.400</td>
<td>1.000</td>
</tr>
<tr>
<td>-0.258</td>
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<td>0.967</td>
<td>0.400</td>
<td>1.000</td>
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<td>-0.385</td>
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<td>0.951</td>
<td>0.402</td>
<td>1.003</td>
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<tr>
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<td>0.950</td>
<td>0.411</td>
<td>1.019</td>
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<td>0.962</td>
<td>0.430</td>
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<td>0.459</td>
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<td>0.499</td>
<td>1.155</td>
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<td>1.284</td>
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<td>0.635</td>
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<td>0.642</td>
<td>1.284</td>
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<tr>
<td>-2.182</td>
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<td>1.284</td>
<td>0.642</td>
<td>1.284</td>
</tr>
<tr>
<td>MODEL:</td>
<td>5</td>
<td>6</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>-------</td>
<td>----</td>
<td>----</td>
<td>----</td>
<td>----</td>
</tr>
<tr>
<td>$\frac{Z}{RT}$</td>
<td>$(\frac{R}{RT})_H$</td>
<td>$(\frac{R}{RT})_T$</td>
<td>$(\frac{R}{RT})_H$</td>
<td>$(\frac{R}{RT})_T$</td>
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<td>0.550</td>
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TABLE II (continued)

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<td>((R/RT))_H</td>
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<td>0.501</td>
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# TABLE III

## TEST RUN SUMMARY

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<th>1.3</th>
<th>1.3</th>
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<th>1.3</th>
<th>1.3</th>
<th>1.2</th>
<th>1.4</th>
<th>1.3</th>
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<tr>
<td>TRAVERSE AXIAL (IN.)</td>
<td>0.1</td>
<td>0.625</td>
<td>1.625</td>
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<td>3.625</td>
<td>4.625</td>
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<td>0.1</td>
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<tr>
<td>DISTANCE (CM.)</td>
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<td>6.668</td>
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<td>X</td>
<td>X</td>
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### MODEL:

- **A1**: X X X X X
- **A2**: X X X X X X
- **A3**: X X X X X
- **A4**: X X X X X
- **A5**: X X X X X
- **A6**: X X X X X X X
- **A7**: X X X X X
- **A8**: X X X X X
- **A9**: X X X X X
- **A10**: X X X X X
- **AE**: X X X
- **S1**: X X X X X
- **S2**: X X X X X
- **S3**: X X X X X
- **S4**: X X X X X
- **S5**: X X X X X
- **S6**: X X X X X
- **S7**: X X X X X
- **S8**: X X X X X
- **S9**: X X X X X
- **S10**: X X X X X
- **SE**: X X X
- **SA2**: X
- **SA6**: X
- **SA10**: X
TABLE IV

Performance Comparisons for Axial, Swirling and Skewed Flow Distributions

<table>
<thead>
<tr>
<th>Model</th>
<th>Average Base Pressure Coefficient</th>
<th>Thrust Coefficient</th>
<th>Flow Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( C_P )</td>
<td>( C_T )</td>
<td>( C_F )</td>
</tr>
<tr>
<td>A2</td>
<td>-.166</td>
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<td>.972</td>
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<td>-.840</td>
<td>.695</td>
<td>.827</td>
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<td>.903</td>
<td>.954</td>
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<td>.888</td>
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TABLE V

Comparison of Test and Theory for Configurations

SA2, SA6, SA10, SE

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<tr>
<th>Model</th>
<th>Average Base Pressure Coefficient</th>
<th>Thrust Coefficient</th>
<th>Flow Coefficient</th>
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<tbody>
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<td>CP2</td>
<td>CT</td>
<td>CF</td>
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<td>0.903</td>
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<td>0.628</td>
<td>0.941</td>
</tr>
</tbody>
</table>

-59-
Figure 1. Analytical Model
Case 1. Parallel Streamlines and \( r_m \neq 0 \)

\[
r = r_m - \frac{(R - R_m)}{\cos \beta_m}
\]

Case 2. Constant Area Between Streamlines and \( r_m = 0 \)

\[
r = \left( \frac{R^2 + R_m^2 \sin^2 \beta_m}{(R^2 - R_m^2) \sin^2 \beta_m} \right)^{1.5}
\]

Figure 2. Streamline Curvature Approximations
Specification Statements

1. Ask for input data

Is R/R = 0?

- yes → Stop
- no → Do preliminary calculations

Estimate starting values for MF, ζ, v2, PLOS

2. Calculate constants in meanline equation

Initialize parameters to values for ζ = 0

10. Calculate normal equilibrium and continuity at successive downstream stations

Calculate R/R and axial forces at stations 1 and 2

Calculate error in R/R and axial force balance

Are both errors ≤ 0.3%?

- yes → Is IPT = 0?
  - yes → More iterations?
    - yes → Select new MF and L
    - no → Subroutine INT2
  - no → no
- no → Is ITR = MAXIT?
  - yes → More iterations?
    - yes → Select new MF and L
    - no → Subroutine INT2
  - no → no

30. Do final calculations and print results

Figure 3. Computer Program Block Diagram
Figure 4. Secant Iteration Scheme
Figure 5. Photograph of the Base Pressure Model Assembly
Figure 6. Photograph of the Axial and Swirl Vane Assemblies
Figure 7. Hub Base Pressure Test Model Schematic
Figure 8. Photograph of the Base Pressure Model Installed in the Test Stand
Figure 9. Schematic of Exhaust Traverse Probe

All units in inches except those in parentheses which are centimeters.
Figure 10. Probe Calibration for Static Pressure
Figure 11. Total and Static Pressure Coefficient Distribution for Models 1 and 2, Axial Flow
Figure 12. Total and Static Pressure Coefficient Distribution for Models 3 and 4, Axial Flow
Figure 13. Total and Static Pressure Coefficient Distribution for Models 5 and 6, Axial Flow
Figure 14. Total and Static Pressure Coefficient Distribution for Models 7 and 8, Axial Flow
Figure 15. Total and Static Pressure Coefficient Distribution for Models 9 and 10, Axial Flow
Figure 16. Total and Static Pressure Coefficient Distribution for Model E, Axial Flow
Figure 17. Total and Static Pressure Coefficient Distribution for Models 1 and 2, Axial Flow
Figure 18. Total and Static Pressure Coefficient Distribution for Models 3 and 4, Axial Flow
Figure 19. Total and Static Pressure Coefficient Distribution for Models 5 and 6, Axial Flow
Figure 20. Total and Static Pressure Coefficient Distribution for Models 7 and 8, Axial Flow
Figure 21. Total and Static Pressure Coefficient Distribution for Models 9 and 10, Axial Flow
Figure 22. Total and Static Pressure Coefficient Distribution for Model E, Axial Flow
Figure 23. Graphical Representation of the Flow Field for Models 1 and 2, Axial Flow
Figure 24. Graphical Representation of the Flow Field for Models 3 and 4, Axial Flow
Figure 25. Graphical Representation of the Flow Field for Models 5 and 6, Axial Flow
Figure 26. Graphical Representation of the Flow Field for Models 7 and 8, Axial Flow
Figure 27. Graphical Representation of the Flow Field for Models 9 and 10, Axial Flow
Figure 28. Graphical Representation of the Flow Field for Model E, Axial Flow
Figure 29. Flow Entrainment Characteristics for Models 1 through 4, Axial Flow
Figure 30. Flow Entrainment Characteristics for Models 5 through 8, Axial Flow
Figure 31. Flow Entrainment Characteristics for Models 9, 10 and AE, Axial Flow
Figure 32. Wake Mixing Loss Characteristics for Models A1 through A4, Axial Flow
Figure 33. Wake Mixing Loss Characteristics for Models 5 through 8, Axial Flow
Figure 34. Wake Mixing Loss Characteristics for Models 9, 10, and AE, Axial Flow
Figure 35. Effects of Geometry on Average Hub Base Pressure, Axial Flow
**Figure 36. Effects of Geometry on Main Flow Thrust Coefficient, Axial Flow**
Figure 37. Effects of Geometry on Overall Thrust, Axial Flow
Figure 38. Effects of Geometry on Flow Coefficient, Axial Flow
Figure 39. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 1 and 2, Swirling Flow, Close-Up Traverse Position.
Figure 40. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 3 and 4, Swirling Flow, Close-Up Traverse Position
Figure 41. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 5 and 6, Swirling Flow, Close-Up Traverse Position

S5
Z/Rₜ = 0.06

S6
Z/Rₜ = 0.06
Figure 42. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 7 and 8, Swirling Flow, Close-Up Traverse Position
Figure 43. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 9 and 10, Swirling Flow, Close-Up Traverse Position
Figure 44. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models E, Swirling Flow, Close-Up Traverse Position.
Figure 45. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 1 and 2, Swirling Flow, Downstream Traverse Location.
Figure 46. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 3 and 4, Swirling Flow, Downstream Traverse Location
Figure 47. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 5 and 6, Swirling Flow, Downstream Traverse Location
Figure 48. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 7 and 8, Swirling Flow, Downstream Traverse Location
Figure 49. Total and Static Pressure Coefficient and Swirl Angle Distribution for Models 9 and 10, Swirling Flow, Downstream Traverse Location.
Figure 50. Total and Static Pressure Coefficient and Swirl Angle Distribution for Model E, Swirling Flow, Downstream Traverse Location.
Figure 5.1 Graphical Representation of the Flow Field for Models 1 and 2, Swirling Flow
Figure 52. Graphical Representation of the Flow Field for Models 3 and 4, Swirling Flow
Figure 53. Graphical Representation of the Flow Field for Models 5 and 6, Swirling Flow
Figure 54. Graphical Representation of the Flow Field for Models 7 and 8, Swirling Flow
Figure 55. Graphical Representation of the Flow Field for Models 9 and 10, Swirling Flow
Figure 56. Graphical Representation of the Flow Field for Model E, Swirling Flow
Figure 57. Flow Entrainment Characteristics for Models 5 through 8, Swirling Flow
Figure 58. Flow Entrainment Characteristics for Models 1 through 4, Swirling Flow
Figure 59. Flow Entrainment Characteristics for Models 9, 10, and E, Swirling Flow
Figure 60. Wake Mixing Loss Characteristics for Models 1 through 4, Swirling Flow
Figure 61. Wake Mixing Loss Characteristics for Models 5 through 8, Swirling Flow
Figure 62. Wake Mixing Loss Characteristics for Models 9, 10 and SE, Swirling Flow
Figure 63. Effects of Geometry on Average Hub Base Pressure, Swirling Flow
Figure 64. Effects of Geometry on the Hub Outer Radius Base Pressure Coefficient, $\beta = 10$ & 0, Swirling Flow
Figure 65. Effects of Geometry on the Hub Outer Radius Base Pressure Coefficient, $\beta = -10$ & $-20$, Swirling Flow
Figure 66. Effects of Geometry on Main Flow Thrust, Swirling Flow
Unstable

Figure 67. Effects of Geometry on Overall Thrust, Swirling Flow
Figure 68. Effects of Geometry on Flow Coefficient, Swirling Flow
Figure 69. Effects of Pressure Ratio on Total and Static Pressure Coefficients and Swirl Distribution for Model 2, Swirling Flow
Figure 70. Effects of Pressure Ratio on Total and Static Pressure Coefficients and Swirl Distribution for Model 6, Swirling Flow
Figure 71. Effects of Pressure Ratio on Total and Static Pressure Coefficients and Swirl Distribution for Model 10, Swirling Flow
Figure 72. Effects of Pressure Ratio on the Average Hub Base Pressure Coefficient, Swirling Flow
Figure 7.3. Effects of Pressure Ratio on the Hub Outer Radius Base Pressure Coefficient, Swirling Flow
Figure 74. Effects of Pressure Ratio on the Main Flow Thrust Coefficient, Swirling Flow
Figure 75. Effects of Pressure Ratio on the Overall Thrust Coefficient, Swirling Flow
Figure 76. Effects of Pressure Ratio on The Flow Coefficient, Swirling Flow
Figure 77. Photograph of the Blockage System Installed in the Test Stand
Figure 78. Effects of Blockage on Total and Static Pressure Coefficients for Model 2, Axial Flow
Figure 79. Effects of Blockage on Total and Static Pressure Coefficients for Model 6, Axial Flow
Figure 80. Effects of Blockage on Total and Static Pressure Coefficients for Model 10, Axial Flow
Figure 81. Effects of Blockage on the Base Pressure and Flow Coefficient for Models 2, 6 and 10, Axial Flow
Figure 82. Effects of Blockage on Total and Static Pressure Coefficients and Swirl Distribution for Model 2, Swirling Flow
Figure 83. Effects of Blockage on Total and Static Pressure Coefficients and Swirl Distribution for Model 6, Swirling Flow
Figure 84. Effects of Blockage on Total and Static Pressure Coefficients and Swirl Distribution for Model 10, Swirling Flow
Figure 85. Effects of Blockage on the Base Pressure Coefficients, Swirling Flow
Figure 86. Effects of Blockage on The Flow Coefficient, Swirling Flow
Figure 87. Total and Static Pressure Coefficient and Swirl Angle Distribution for Model 2, Skewed Flow Distribution
Figure 88. Total and Static Pressure Coefficient and Swirl Angle Distribution for Model 6, Skewed Flow Distribution
Figure 89. Total and Static Pressure Coefficient and Swirl Angle Distribution for Model 10, Skewed Flow Distribution
Figure 90. Angular Momentum Distribution From Test
Figure 91. Wake Area Coefficient
Figure 92. Variation of $C_{PL}$ and $C_9$ with Geometry
Figure 93. Comparison of Theoretical Predictions to Test Results for the Base Pressure, Flow and Thrust Coefficients, $R_{H}/R_{T} = 0.40$, Swirling Flow
Figure 94. Comparison of Theoretical Predictions to Test Results for the Base Pressure, Flow and Thrust Coefficients, $R_{H}/R_{T}=0.55$, Swirling Flow
Figure 95. Comparison of Theoretical Predictions to Test Results for the Base Pressure, Flow and Thrust Coefficients, \( R_H/R_T = 0.70 \), Swirling Flow
Figure 96. Comparison of Theoretical Predictions to Test Results for the Base Pressure, Flow and Thrust Coefficients, \( R_H/R_T = 0.40 \), Axial Flow
Figure 97. Comparison of Theoretical Predictions to Test Results for Base Pressure, Flow and Thrust Coefficients, \( R_{H}/R_{T} = 0.55 \), Axial Flow
Figure 98. Comparison of Theoretical Predictions to Test Results for Base Pressure, Flow and Thrust Coefficients, \( \frac{R_H}{R_T} = 0.70 \), Axial Flow